

Transitioning to **CLIMATE ACTION**

Roshnie A. Doon (Ed.)

Transitioning to **Climate Action**

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Dedication

I dedicate this book to both my parents, whose unwavering guidance has instilled in me the essential values of courage and humility in the pursuit of my dreams.

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About the Editor

Dr. Roshnie A. Doon is the Secretary of the Caribbean Academy of Sciences (CAS) Regional Executive at The University of the West Indies (UWI), St. Augustine, Trinidad and Tobago. In this role, she oversees all chapters across the Caribbean, including those in Trinidad and Tobago, Guyana, Jamaica, Guadeloupe, Antigua and Barbuda, and Barbados. Additionally, she is a research affiliate with the Global Labor Organization (GLO) in Essen, Germany, where her primary area of expertise lies in Labor Economics.

Dr. Doon earned her PhD in Economic Development Policy, an MSc in Economics, and a BSc in Economics from UWI, St. Augustine, Trinidad and Tobago. She also completed a PhD Masterclass in International Business at the Henley Business School at the University of Reading, United Kingdom. Throughout her academic career, she has received several prestigious awards, including the Mannic Bissoon Memorial Scholarship, UWI Postgraduate Scholarship, and Undergraduate Bursary. Additionally, she was honored with the World Society Foundation (WSF) and Council for European Studies (CES) Global Digital Fellowship. Dr. Doon has also benefited from various research grants, such as the Campus Research and Publication Fund at UWI St. Augustine and the Knowledge Unlatched (KU) Publication Fund in Berlin, Germany.

Dr. Doon serves on the editorial boards of several publications, including the International Journal of Law and Policy, Discover Global Society, and the International Journal of Applied Business and International Management. She is affiliated with numerous prestigious institutions, such as the International Science Council (ISC) in Paris, France, the Inter-Academy Partnership (IAP) in Trieste, Italy, as well as the Industrial Engineering and Management (IEM) and the Technological Transfer Management (TTM) Research Cluster in St. Augustine, Trinidad and Tobago. Dr. Doon currently leads six research clusters focused on labor economics, social policy, migration, COVID-19, climate change, and Industry 4.0, publishing several articles and books in these fields. Additionally, she has presented her research findings at various conferences around the world, including locations in Iceland, Italy, Australia, Pakistan, the United States, the United Kingdom, Guyana, Jamaica, Trinidad and Tobago, and Barbados.

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Abstracts

Preface to Transitioning to Climate Action
by Roshnie A. Doon

Climate action is of crucial importance for countries around the world because it focuses on the urgent need for and implementation of adaptation and mitigation measures to reduce the adverse effects of severe climate change events. This edited volume was inspired by the fact that climate action not only helps to create a cleaner environment but is also one of the main drivers of innovation and competitiveness of global economies through the creation of sustainable jobs and renewable energy sources. Due to the interconnected nature of the Sustainable Development Goals (SDGs), taking initiative towards climate action is also a means to safeguard the livelihoods of many vulnerable populations against food insecurity, socioeconomic inequality, and intergenerational poverty. This edited volume, made possible by the contributions of several scholars around the world, highlights the significance of addressing climate change, including the reduction in greenhouse gases (GHGs) and the development of renewable energy resources. Additionally, it explores the implications of climate change on other SDGs, including poverty, food production, and gender-based violence. It is anticipated that this edited volume will be a valuable resource for policymakers, researchers, scientists, activists, international organizations, and other key stakeholders who are engaged in promoting climate action and sustainable development.

The Climate Change and Poverty Nexus: Trade-Offs and Synergies between Poverty and Climate Action
by Oluwadamilola Adeola Oyadeyi and Olajide O. Oyadeyi

This chapter examines the relationship between climate action and poverty, highlighting the need to address the trade-offs and synergies between these two complex challenges. As the world grapples with the urgent need to mitigate climate change and alleviate poverty, it becomes increasingly apparent that both goals are intricately intertwined, frequently presenting significant trade-offs and opportunities for synergistic solutions. The chapter draws on a review of existing case studies from five countries, each located in a different global region: the Bahamas (Latin America and the Caribbean), Japan (Asia), Norway (Europe), Egypt

(Africa), and the United Arab Emirates (the Middle East). The rationale for selecting these countries within the respective regions is that they adopt unique climate-action strategies in developing their respective economies. At the same time, each uses climate change to tackle poverty. The analysis relies on secondary sources and published studies, rather than original fieldwork, to examine how climate actions have been designed and implemented to tackle poverty in each context. The findings suggest that many of the most vulnerable and marginalised populations around the globe are disproportionately impacted by the adverse effects of climate change. These communities, which are frequently trapped in a cycle of poverty, confront elevated risks from extreme weather events, rising sea levels, and shifting agricultural conditions. Furthermore, climate change can exacerbate poverty if not carefully managed. The chapter also reviews potential synergies between climate action and poverty reduction. It highlights instances where well-designed climate initiatives have simultaneously reduced poverty, increased resilience, and improved livelihoods. Community-based renewable energy projects, sustainable agricultural practices, and climate-smart urban planning are examples of initiatives that can generate employment and stimulate economic growth. In conclusion, this chapter emphasises the need to scrutinise climate action through the lens of poverty, recognising the trade-offs and opportunities and providing guidance for policymakers, researchers, and practitioners navigating the complex nexus of climate action and poverty.

The Adoption and Scaling of Stress-Tolerant Rice Varieties: A Sustainable Climate Adaptation Strategy for Smallholders

by Swati Nayak, Neeraj Kumar Tyagi, Jami Naveen, Suryakanta Khandai, S. K. Mosharaf Hossain, Ashish Kumar Srivastava, Virendar Kumar and Sudhanshu Singh

Climate change hastens the degradation of ecosystems and has a detrimental influence on food production and the food chain. There is a decline in agricultural productivity owing to stress incidences, accentuated by the increasing variability in inter-annual and seasonal climatic patterns. This has made the smallholder paddy farmers of Assam extremely vulnerable. One of the prominent abiotic stresses in Assam is recurrent submergence, which poses a substantial challenge to rice cultivation in flood-prone regions during the Sali/wet season. Drought is also a significant abiotic stress for Assam, particularly for Sali rice, because of the increasing frequency and duration of dry spells. In addition to Sali rice, Boro/summer rice is also confronted with various other stresses. Boro rice is vulnerable to cold stress in the early stages and heat stress later, impacting productivity. Losing a crop season

is detrimental to farmers' livelihoods and the food system's sustainability. Hence, it is critical to address low productivity in areas where extreme weather events are widespread and recurrent. The enhancement in abiotic stress tolerance in rice can potentially augment the production, productivity, and overall profitability of the food system. Therefore, it is crucial to adopt an appropriate adaptation strategy to overcome this threat. With seeds being a primary and essential input, the adoption of stress-tolerant rice varieties is a high-potential and highly affordable adaptation strategy to combat climate risks. The adoption and scaling of stress-tolerant rice varieties (STRVs) can be one of the most significant climatic risk adaptation approaches for the future.

Best Agronomic Practices to Mitigate the Transition of Climate Action

by Anjana J. Atapattu, Shashi S. Udumann, Nuwandhya S. Dissanayaka, Tharindu D. Nuwarapaksha, Aruna S. B. Dissanayake, Asanka Tennakoon, Dissanayake M. D. Rasika, D. H. B. R. Dassanayake, Jayampathi Ekanayake, S. M. C. B. Karalliyadda, N. P. S. N. Bandara, J. K. Sajeep Sankalpa, S. Vinujan, Amila C. Gama Arachchige and Dushan P. Kumarathunge

Climate change poses significant obstacles to agriculture, compounded by conventional farming practices that release greenhouse gases. However, adopting sustainable agronomic practices shows promise in tackling climate change impacts and promoting more resilient agricultural systems. There is a lack of comprehensive synthesis that integrates these agronomic practices specifically under the framework of nature-based solutions and evaluates their multifunctional roles in climate mitigation, resilience building, and ecosystem restoration. This study analyzes evidence on various agronomic solutions to minimize climate change's negative effects. Practices such as minimal soil disturbance, continuous soil cover, improved nutrient cycling, agroforestry, organic farming, carbon farming, crop diversification, crop rotation, intercropping, cover cropping, integrated pest management, drought-tolerant crop varieties, and soil health management, mulching, and precision agriculture technologies (e.g., variable rate application, remote sensing, AI-based decision tools) can be identified as the best agronomic practices to enhance the resilience of farming systems to climate-related stressors. Other than that, these practices will help maximize the crop yield, biodiversity conservation, and farmer income. However, numerous social, economic, educational, and institutional barriers exist to the successful adaptation of climate-

smart agronomic best practices. The scientific consensus, coupled with a growing body of practical experience, underscores the urgency and feasibility of scaling sustainable agronomy on a global scale. The development of integrated platforms represents the most transformative future direction, creating unified systems that connect all farm technologies to make coordinated decisions that improve both crop yields and climate benefits.

Climate Change Perception and Adaptation Behaviours Among Root and Tuber Crop Farmers: Towards Improving Climate Action in Agriculture

by Oral O. Daley, Albertha Joseph-Alexander, Wendy-Ann P. Isaac and Ronald R. Roopnarine

Farmers play a pivotal role in the urgent action required to address the negative impact of climate change on global agriculture. Additionally, improving climate action in agriculture requires an assessment of farmers' awareness of climate change and their response to it. Furthermore, it is important to assess this in vulnerable regions of the world and for vulnerable crops like roots and tubers. This study explored climate change perceptions and adaptation behaviours among 82 root and tuber crop farmers in Trinidad and Tobago. The findings indicated a strong awareness among farmers of the escalating impacts of climate change, with significant reports of increased drought (84%), flooding (69%), and rainfall intensity (66%). Farmers' perceptions of climate-related outcomes were significantly associated with education level ($p = 0.032$), combined monthly household income ($p < 0.001$), household size ($p \leq 0.001$), and the frequency of extension visits ($p < 0.05$). Adaptation strategies included the adoption of new irrigation systems, increased use of fertilizers, and diversification of farm income. This study underscores the need for more tailored extension services to effectively communicate and facilitate the implementation of climate change adaptation strategies across diverse farming demographics and contributes to the broader discourse on sustainable climate action.

Climate Change-Induced Gender-Based Violence (GBV) Against Men and Boys in the Caribbean

by Roshnie A. Doon

The phenomenon of gender-based violence (GBV) is often synonymous with the violation of human rights and gender inequality. In the Caribbean, as in other parts of the world, GBV can manifest itself in either physical, sexual, psychological, or economic forms. The GBV literature often portrays persons experiencing such abuse as women and girls, and the perpetrators as men and boys. However, male victims who experience GBV often experience similar types of abuse to women and girls, but their reasons for staying in their abusive relationship tend to vary. These reasons span a wide spectrum from societal and cultural norms to the potential stigma attached to being a male victim, which in the context of climate change events often serves to marginalize male victims. Given that the Caribbean is particularly vulnerable to climate change events, this chapter aims to explore the presence of climate change-induced GBV against men and boys in the Caribbean. Using a conceptual research methodology, this chapter will examine not only the link between the two areas but also the role that climate change plays in worsening GBV against men and boys in the Caribbean, as well as barriers and solutions to addressing such violence during climate change events.

Towards a Climate-Resilient World: The Role of Renewable Energy, Innovation, and High-Tech

by Pascaline Nyirabuhoro and Jean Claude Ndayishimiye

The escalating threats posed by climate change to ecosystems, biodiversity, and human society underscore the urgent need for a decisive shift away from dependence on fossil fuels. This review underlines the central role of renewable energy, innovation, and high-tech in building a climate-resilient world and achieving sustainable development goals. Renewable energy emerges as an alternative that not only supports carbon-neutral economic activities but also helps mitigate climate change. Solar energy, captured through PV cells and CSP systems, has gained significant attention, leading to improvements in both efficiency and scalability. Advances in wind turbine design for both small- and large-scale applications, along with improvements in materials, have significantly enhanced the capture of kinetic energy at a relatively low cost, making wind power an

increasingly competitive source of clean energy. Advances in hydropower turbine, dam, and pump design, particularly for large-scale applications, have positioned hydropower as a strategic tool for stabilizing intermittency in renewable energy, specifically through hydroenergy storage. Advances in energy storage, along with their integration into electrical grids, have demonstrated the potential to address the intermittency of renewable energy, thereby paving the way for more stable energy systems and reduced dependence on conventional energy sources. Overall, renewable energy, innovation, and high-tech are bringing society closer to a more climate-resilient world where clean energy plays a central role in mitigating climate change, adapting to its impacts, and achieving climate neutrality.

Climate Policy Reform Through the Indigenous Lens of the Institutional Analysis and Development Framework: A Case of the Bangladeshi Santals

by Parimal Kumar Roy

This chapter's objective is to critically evaluate Bangladesh's policy reforms on climate change, aligning with the Indigenous lens. Bangladesh is indeed a melting pot of Indigenous communities; there are fifty Indigenous groups. For example, the Santals is one of those groups who live in the northern part of the country, and they are in a vulnerable position due to climate change. With the help of the Indigenous lens, we are able to look at the lifeworld instead of worldview by implementing different policies, acts, and laws. This study uses a methodologically qualitative approach and ethnographic design, followed by the neoliberal trend to contemplate government initiatives to ensure SDG 13. Consequently, this study explores the policy loopholes and development framework's caveats for Indigenous people's viability. Considering the result, the author recommends using an Indigenous Community Perspective model to uphold their sustainability under Agenda 21.

Climate Uncertainty Index for Pakistan and Its Nexus with Carbon Emissions and Growth

by Mahrukh Rauf And Mumtaz Ahmed

Climate change is a worldwide concern, with numerous studies on its impact on different economies. A recently developed climate policy uncertainty index for the United States inspires practitioners across the globe to adapt or develop similar

indices for other countries. At present, Pakistan lacks such an index. The present study takes the lead and develops a climate uncertainty index (CUI) for Pakistan by quantifying public concerns and uncertainties about climate issues in Pakistan using Google Trends data. In addition, this study examines the relationship between current global issues, such as carbon dioxide emissions, global warming, and the degradation of the environment, as well as web searches related to climate and climate uncertainty.

Financing the Transformation into the World's First Climate-Resilient Country: The Climate–Debt Nexus in Dominica

by Jwala Rambarran

Dominica faces a climate–sovereign debt doom loop. The resources which Dominica urgently needs to invest in becoming the world's first climate-resilient country are increasingly being diverted to repay debts, while its borrowing costs are rising partly due to climate-related vulnerabilities, leading to the country ranking amongst the top ten most heavily indebted Small Island Developing States (SIDSs). This Chapter highlights how financial mechanisms such as debt pause clauses, parametric insurance for sovereign debt, sovereign debt restructuring, and debt-for-climate swaps could mitigate the risks associated with the climate–debt nexus, easing liquidity pressures and unlocking fiscal space to fund climate resilience projects. Nevertheless, for countries with unsustainable debt, such as Dominica, these financial instruments would need to be part of a wider package of reforms to the global debt architecture. This will require future research on how the international community can improve Dominica's access to mostly concessional long-term financing for its climate resilience strategy. Further studies would also be needed on the necessary reforms to the global financial architecture which would support Dominica and other high-debt, climate-vulnerable countries in addressing their interlinked climate–debt nexus.

Community-Oriented Climate Action Plan in a Mid-Sized Shoreline Municipality: A Canadian Case Study

by Negin Ficzkowski, Gail Krantzberg, Arash Golshan, Yagiz Ercin, Umais Abdull Baqi, Sufiyan Bharucha, Sadiyah Manidhar and Mateo Orrantia

A municipal climate action plan outlines programs and policies for effective greenhouse gas emission reductions and iterative adaptation strategies based on local priorities and realities. In this study, we supported a shoreline municipality in Canada through the development of a community-based climate action initiative. This initiative combined public workshops and a rapid online survey informed by interviews with local thought leaders and institutional authorities in the region. The project followed a multistage comparative analysis to assess active knowledge and the perception of climate change impacts among community members. Our findings were synthesized into a set of recommendations for integrating community expectations into municipal planning, thereby enhancing the legitimacy and responsiveness of local action plans. The primary objective of this project was to enable, empower, and educate residents to co-create a climate action plan grounded in their lived realities and priorities. This chapter outlines the methodological approach in detail, offering a transferable model for other coastal communities seeking to bolster public trust, local capacity, and collective ownership in climate governance. By prioritizing accessible and inclusive engagement strategies, this case study demonstrates how localized planning can address the complex, overlapping mandates faced by coastal communities under threat from climate change.

Towards 2030: The Effective Employment of ICTs in Influencing Climate Action Among Rural Communities

by Sharon Tshipa and Olekae T. Thakadu

Frequent and extreme weather events indicate that the globe is nearing catastrophic tipping points. A viable solution climate science suggests is an urgent transition to a safe operating space within planetary boundaries. Achieving this desirable 'Holocene state' calls for climate action that is inclusive of the most vulnerable rural poor. To ensure inclusivity, global leaders have taken advantage of the proliferation of information communication technologies (ICTs) to communicate practical adaptation and mitigation measures. This chapter, therefore, investigates effective pathways of employing ICTs in influencing climate action. Conducted among Okavango Delta communities, this study utilised a convergent parallel

mixed-methods design. Survey instruments were administered to 303 randomly sampled household respondents and 21 purposively sampled key informants. The collected data were analysed using qualitative methods such as content and thematic analysis and statistical procedures such as descriptive and inferential statistics. The results showed that regardless of the climate change awareness messages received by residents regularly through diverse ICT channels, rural communities are still not satisfactorily aware of the climate change phenomena, a factor thwarting the localisation of the SDGs. To address this, the study found that there is a need for development stakeholders to diversify climate change messages, moving from the predominant agriculture focus to supporting climate actions in cross-cutting sectors.

Understanding Climate Action Perceptions in the Caribbean: Harnessing Machine Learning Insights

by Letetia M. Addison, Trevon Tewari, Sabina Gooljar and Patrick Hosein

Amid the global urgency for sustainability, the Caribbean faces unique climate challenges that may not be fully understood by the general public. Addressing this requires assessing current public sentiments and understanding of climate change impacts on daily life. Traditional approaches to gauging climate attitudes in the Caribbean have limitations, which Machine Learning (ML) techniques can help overcome. ML can analyse large, diverse datasets—such as social media, surveys, and public discourse—to reveal nuanced insights that conventional methods may miss. These insights and their underlying drivers can inform targeted communication and policy interventions. This chapter investigates Caribbean attitudes toward climate action and presents an ML-based framework to enhance the climate feedback loop, enabling more effective strategies to educate the public and counter misinformation. The study prioritises explanatory ML techniques—including sentiment analysis, topic modelling, and clustering—to uncover key themes shaping climate perceptions. Applications of Large Language Models (LLMs) and intelligent agents are explored to expand the reach of perception analysis across dialects and demographics. Findings are translated into actionable policy recommendations through collaboration with local agencies. Ethical considerations, including data privacy and representational fairness, are addressed through anonymisation and community-informed model validation. Ultimately, this approach supports a collective shift toward sustainable practices, enhancing climate resilience across Caribbean Small Island Developing States (SIDS).



Preface to Transitioning to Climate Action

Roshnie Anita Doon

1. Introduction

Sustainable development is one of the most essential avenues used by countries worldwide to address a multitude of problems such as poverty, hunger, food insecurity, poor education and healthcare outcomes, gender inequality, and limited access to clean water and an affordable source of energy (UNDP n.d.a). Through the concept of sustainable development, these problems have been addressed throughout the literature by scholars such as Strezov et al. (2016) by assessing the social, economic, and environmental dimensions of sustainable development using various tools, such as indices like the Human Development Index (HDI), to provide a holistic and innovative solution to these problems, while harmonizing these dimensions. Sustainable development would not only have significant environmental benefits such as supporting countries to preserve and manage their natural resources more efficiently but also foster the continued manifestation of economic benefits such as supporting vulnerable communities to build their local economic development, and domestic economies to become more innovative by investing (Abrahams 2005). These investments would not only stimulate economic growth and increase productivity, but also reduce operating costs while improving efficiency and profitability.

One of the global problems that threatens to disrupt the mission of sustainable development is that of climate change, where the latter has become one of the most defining issues of the 21st century, as the continuous shift in climate change patterns, demonstrated by rising temperatures and sea levels, as well as amplified storms, has led to the frequent prevalence of catastrophic natural disasters (NOAA-NCEI 2025). This, in turn, has exacerbated the existing vulnerabilities of communities, particularly those in Small Island Developing States (SIDSs) and resource-poor developing countries, pushing them into deeper levels of extreme poverty, as it has threatened to become the main cause of mass malnutrition, famine, social exclusion, and displacement, as well as socio-economic and political instability (WB 2023; Singh et al. 2024).

As the world continues to experience record-breaking changes in climate patterns and extreme natural disasters, countries must begin taking proactive steps towards addressing their role in these events by reducing their carbon footprint and taking responsibility for the negative implications of these events for the challenges

of sustainable development. As Anukwonke et al. (2022) argue, if climate change outcomes are not addressed, they can lead to economic hardship across generations, perpetuating cycles of intergenerational poverty and inequality.

2. Moving Towards Climate-Conscious Solutions

Considering the potential adverse effects of climate change on the lives and livelihoods of future generations, climate action is explicitly addressed in the United Nations' Sustainable Development Goal 13 (UN n.d.a). This goal is one of the 17 Sustainable Development Goals (SDGs) established during the United Nations' (UN's) Conference on Sustainable Development held in Rio de Janeiro, Brazil, in 2012 (UN n.d.a). These goals were later adopted by all UN member states in 2015 at the UN Summit in New York, United States, and enforced in 2016 as part of the 2030 Agenda for Sustainable Development, which aims to address a multitude of problems experienced by the most vulnerable in society such as poverty, food insecurity, the adverse effects of climate change, disparities in healthcare, political instability, and inequality (UNDP n.d.b; UN n.d.b).

Goal 13 of the Sustainable Development Goals (SDGs) calls on all UN member countries to act against climate change and its negative effects. This goal emphasizes the urgent need for global collaboration to mitigate climate change's effects, adapt to its impacts, and promote sustainable practices using targeted objectives, whose intention is to strengthen resilience to and adaptive capacity for climate-related hazards, integrate climate change-related measures into national policies and planning, and improve education and awareness, human and institutional capacity for climate change mitigation, and adaptation (The Global Goals n.d.)

This book provides an in-depth analysis of studies related to Sustainable Development Goal 13 (SDG 13), which focuses on climate action, and explores its vital connections to several other Sustainable Development Goals. Through comprehensive research, this book underscores the critical need for effective strategies to mitigate climate change and adapt to its impacts, by highlighting the urgency of addressing the adverse consequences of climate change, such as increasing food insecurity, economic disparities, and social inequalities, all of which threaten progress in the interconnected SDGs (UNEP 2023).

By illustrating these complex interdependencies, this book advocates for integrated approaches that recognize and tackle the multifaceted challenges posed by climate change for sustainable development, as countries around the world are significantly off track to achieve the 2030 deadline for the SDGs. These studies, which go on to focus on climate action and its connection to other Sustainable

Development Goals (SDGs), are crucial for member countries in achieving their Sustainable Development Agenda. This is because (1) climate change events tend to have a global impact, often exceeding national boundaries, (2) the negative effects of climate change can hinder progress in other SDGs, potentially leading to intergenerational poverty, and (3) research on SDG 13 and its relationships with other SDGs can inspire the development of innovative solutions that can be implemented globally (Fuso Nerini et al. 2019).

3. Highlights

The chapters within this book contain a wide range of information related directly to SDG 13, as well as its connection to other SDGs. For this book, climate action is discussed, concerning specific problems such as poverty (SDG 1—No Poverty), food production (SDG 2—Zero Hunger), gender-based violence (SDG 5—Gender Equality), and renewable energy (SDG 7—Affordable and Clean Energy), as well as focusing exclusively on climate action (SDG 13) by the advancement of climate change policy reforms, the development of a climate uncertainty index, encouraging climate financing, and creating climate change action plans based on the use of Information and Communications Technology (ICT) and Industry 4.0-based technologies.

Some of the captivating highlights from different chapters of this book are as follows:

- Climate Action and No Poverty (SDG 1): Oluwadamilola Oyadeyi and Olajide Oyadeyi's discussion on Climate Change and Poverty Nexus: Trade-offs and Synergies between Poverty and Climate Action highlights how many vulnerable and marginalized groups are severely impacted by climate change events. They examine the trade-offs associated with various climate change mitigation and adaptation strategies and review potential synergies between climate-based action and poverty reduction. They focus on instances where climate-based initiatives have successfully reduced poverty and increased resilience to climate change.
- Climate Action and Zero Hunger (SDG 2): Anjana Atapattu and his colleagues' discussion on Best Agronomic Practices to Mitigate Transition of Climate Action reveals that techniques such as conservation agriculture, agroforestry, and diversification in farming not only act as windbreakers but also assist in isolating carbon dioxide and reduce water and sediment runoff. These practices, in turn, are found to enhance resilience to climate change variability.

- Climate Action and Gender Equality (SDG 5): Roshnie A. Doon, through her discussion on Climate Change-Induced Male Gender Based Violence (GBV) in the Caribbean, explains that while the GBV literature traditionally portrays women and girls as being the main victims of such abuse, men may also experience such violence during climate-related events. Adverse climate change events, such as extreme weather conditions, rising sea levels, and prolonged droughts, can significantly impact the lives of individuals. These events often victimize men, particularly those from vulnerable groups such as low-income communities in the Caribbean. As a result of these changes, many men in the Caribbean may find themselves displaced from their homes and livelihoods, facing increased hardships and challenges in seeking safety and stability during and after the occurrence of natural disasters. The intersection of gender and vulnerability highlights the urgent need for targeted support and intervention for those affected.
- Climate Action and Affordable and Clean Energy (SDG 7): Pascaline Nyirabuhoro and Jean Claude Ndayishimiye, in their chapter on Innovating for a Climate-Resilient World: Renewable Energy and Sustainable Technologies, discuss the importance of innovation in renewable energy and the role that it plays in achieving the SDGs, while mitigating climate change events.
- Climate Action (SDG 13): In this section, the authors highlight some of the most important aspects of climate action, such as climate financing, the development of climate action plans, and the use of Industry 4.0 technologies and ICT. Jawala Ramberran, in his chapter on Financing the Transition to the World's First Climate Resilient Country: The Case of Dominica, speaks about the importance of climate-related financing solutions for SIDSs such as Dominica that are resource-poor and have heavy debt burdens. Negin Fickowski and colleagues, in their chapter on Community-Oriented Climate Action Plan in a Mid-Sized Shoreline Municipality: A Canadian Case Study, show how the design and implementation of such plans are not only effective at reducing greenhouse gas emissions but are critical to bringing awareness to and educating coastal communities on the risk of climate change events. Finally, Sharon Tshipa and Letetia Addison together with their colleagues in their respective chapters demonstrate how (1) ICT can be used to educate communities about climate change mitigation and adaptation plans in the Okavango Delta, Botswana, and (2) Industry 4.0 technologies such as machine learning can be used to better understand public perceptions of climate change mitigation and adaptation plans in the Caribbean region.

4. Conclusions

As the world confronts a climate crisis, collections of articles like those presented in this book are essential, particularly because catastrophic storms, intense droughts, and severe wildfires tend to have a widespread impact, resulting in the need for urgent action. Further, given that climate change is a global challenge that requires a coordinated response from countries worldwide, there is a need to first enhance the resilience and adaptive capacity of countries through effective policy development and integration and second develop both technological and smart solutions to combat climate change. What makes this book unusual and worth reading is its ability to address such a global challenge of climate change from a multidisciplinary perspective.

This book puts forward several studies, from several countries from the Global South, such as Trinidad and Tobago, Dominica, Bangladesh, Botswana, Pakistan, and India, as well as the Global North, such as Canada. This book covers a broad range of research topics, including poverty, agriculture, gender-based violence, renewable energy, climate policy, climate financing, and climate change technologies. These topics are directly related to Sustainable Development Goal (SDG) 13 and demonstrate its interconnectedness with other SDGs. As a result, this book is of great interest to policymakers, researchers, scientists, activists, international organizations, and other key stakeholders who are actively engaged in supporting climate action and sustainable development.

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The Climate Change and Poverty Nexus: Trade-Offs and Synergies Between Poverty and Climate Action

Oluwadamilola Adeola Oyadeyi and Olajide O. Oyadeyi

1. Introduction

The 21st century continues to witness a convergence of global challenges, with climate change emerging as one of the most critical threats to human development and environmental stability. Primarily driven by anthropogenic activities, climate change disrupts weather systems, alters ecosystems, and raises sea levels (Trenberth 2018). These disruptions extend far beyond environmental degradation—they now pose serious challenges to economic growth, public health, social protection systems, and human security.

Least-developed countries (LDCs) and Small Island Developing States (SIDS) are especially vulnerable, as they face significant threats to their livelihoods, food security, and national survival (Ebrahim et al. 2021; Oyadeyi et al. 2024a; Oyadeyi 2025a). According to the Intergovernmental Panel on Climate Change (IPCC), global average temperatures have already risen by more than 1 °C above pre-industrial levels, with projections indicating further increases if mitigation efforts remain insufficient (Uprety et al. 2019; Bush 2020; Marques 2020). This change has translated into a higher incidence of extreme weather events, prolonged droughts, intense flooding, and other climate-related hazards. These events not only displace populations and destroy infrastructure but also intensify poverty, hunger, and inequalities—especially among marginalised communities (Petzold et al. 2019; Marques 2020; Oyadeyi et al. 2024c).

Climate change now operates as a poverty multiplier. It disproportionately affects vulnerable populations, particularly in developing nations with limited adaptive capacity (National Research Council et al. 2011). The World Bank estimates that, without effective climate policies, over 100 million people could fall into extreme poverty by 2030 due to climate-induced shocks (Ebrahim et al. 2021). In regions where agriculture forms the backbone of livelihoods, environmental stressors can drive food insecurity, increase malnutrition, and limit access to essential services such as water, sanitation, education, and healthcare (Thomas et al. 2020). These impacts undermine progress towards long-term sustainable development, creating a vicious cycle of deprivation and vulnerability.

Recognising the severity of this challenge, the international community has prioritised climate action through Sustainable Development Goal 13 (SDG 13), which calls for urgent action to combat climate change and its impacts. SDG 13 emphasises the need to strengthen resilience, integrate climate measures into national policies, and promote education, awareness, and institutional capacity on climate-change mitigation and adaptation. However, climate action must account for its intersection with poverty to be genuinely effective and equitable. There is growing recognition that strategies addressing climate change must simultaneously aim to reduce poverty and promote inclusive development (Petzold et al. 2019; Marques 2020; Oyadeyi 2024a; Oyadeyi 2024b).

This chapter contributes to this growing discourse by reviewing the complex relationship between climate action and poverty. It specifically examines the trade-offs and synergies between these two development goals through a literature-based review of case studies. It draws on secondary data and existing academic and policy literature to analyse how selected countries have responded to climate challenges in ways that seek to address poverty.

Five countries were selected to represent different global regions and development trajectories: the Bahamas (Latin America and the Caribbean), Japan (Asia), Norway (Europe), Egypt (Africa), and the United Arab Emirates (the Middle East). These countries were chosen for their diverse economic statuses and distinct climate-policy approaches. For example, the Bahamas focuses on climate adaptation, the UAE invests in clean energy and technology, Egypt combines mitigation and adaptation with a focus on green employment, Norway provides substantial climate finance, and Japan leads innovation and disaster preparedness.

The review of these case studies provides valuable insights into the diverse policy tools, institutional frameworks, and community-based approaches countries have employed to address climate change while reducing poverty. It identifies the challenges and opportunities embedded in climate policy and demonstrates how well-designed initiatives can produce co-benefits—improving resilience, generating employment, and supporting sustainable development.

This chapter is structured as follows: Section 2 reviews the literature on the climate–poverty nexus. Section 3 presents the selected case studies in detail. Section 4 explores practical solutions and policy implications from the reviewed evidence. Section 6 concludes with reflections and recommendations for policymakers, development practitioners, and scholars seeking to build a more just and sustainable future.

2. Literature Review and Theoretical Framework

Climate change and global warming are increasingly recognised as critical challenges confronting societies worldwide. The scientific consensus attributes these phenomena primarily to anthropogenic activities, notably the burning of fossil fuels, which has led to elevated concentrations of greenhouse gases (GHGs) in the atmosphere (Trenberth 2018; Ebrahim et al. 2021). This alteration in atmospheric composition has been associated with a range of climatic disruptions, including sea-level rise, an increased frequency of extreme weather events, and changing precipitation patterns (Marques 2020).

The evolving nature of these impacts has necessitated a coordinated international response, mainly through multilateral environmental agreements. Frameworks such as the Stockholm Declaration (1972), Montreal Protocol (1987), Kyoto Protocol (1997), and most recently, the Paris Agreement (2015) illustrate a trajectory of global efforts to reduce environmental harm while encouraging states to commit to specific emission-reduction targets (Cai et al. 2013). These agreements also reflect broader shifts in environmental governance, where climate-change mitigation is framed as a scientific and socio-political priority.

In this context, trade agreements and climate-policy instruments have increasingly been examined in the literature for their potential to contribute to or undermine global climate action. Scholars have debated how economic liberalisation, trade facilitation, and environmental sustainability coexist within existing governance frameworks (Oyadeyi et al. 2024b; Oyadeyi and Oyadeyi 2025). The literature highlights a growing interest in policy integration, where climate goals are embedded within trade mechanisms or development planning to align global economic and environmental objectives.

This section, therefore, provides a thematic review of the academic and policy literature on climate-change governance, with particular attention to how trade agreements and national climate policies are employed to address environmental challenges. The review also engages with theoretical perspectives on policy coherence and institutional integration, which offer insight into how international agreements and domestic strategies interact with the broader goal of sustainable development. This framing helps to contextualise the case studies that follow and to identify the central conceptual debates relevant to the climate change–poverty nexus.

2.1. The Relationship Between Climate Change and Poverty

Existing studies have established the complex and mutually reinforcing relationship between climate change and poverty. Climate change is increasingly

recognised as a significant threat multiplier, exacerbating pre-existing social and economic inequalities and disproportionately affecting low-income and marginalised populations (Hallegatte et al. 2018; Soergel et al. 2021). Over two billion people, approximately one-third of the global population, live in poverty or near the poverty threshold (Streimikiene et al. 2020; Oyadeyi 2025b). These groups are particularly vulnerable to climate-related hazards such as droughts, floods, and extreme temperatures due to exposure, limited adaptive capacity, and socioeconomic precarity (Yang and Percival 2009; Khanal et al. 2021).

The projected implications of climate change for poverty are significant. According to various estimates, climate change could push over 100 million people back into extreme poverty by 2030 (Khanal et al. 2021), while over 200 million individuals may face displacement due to the increased frequency and severity of climate-induced disasters (Cai et al. 2013). The spatial and socioeconomic distribution of vulnerability is particularly pronounced in low-income countries and regions highly dependent on climate-sensitive sectors such as agriculture and fisheries (Petzold et al. 2019; Hallegatte et al. 2020).

Structural inequalities are critical in shaping exposure and sensitivity to climate risks. Poor communities are more likely to reside in high-risk areas, including informal settlements in floodplains and coastal zones, and often lack access to adequate infrastructure, early warning systems, and financial safety nets (Streimikiene et al. 2020). In this context, climate change reinforces the barriers to economic mobility, social protection, and long-term well-being, thereby contributing to persistent cycles of deprivation (Soergel et al. 2021).

In response, the concept of Adaptive Social Protection (ASP) has emerged as a framework for integrating social protection systems with climate-resilience strategies. ASP encompasses policies and programmes that aim to strengthen the capacity of vulnerable populations to anticipate, absorb, and recover from climate-related shocks (Aleksandrova 2020). Examples include targeted cash transfers that support livelihoods during periods of disruption, food and water subsidies during climate-induced scarcity, and weather-indexed insurance mechanisms tailored to agricultural producers facing droughts or floods (Hallegatte et al. 2018; Soergel et al. 2021). Investments in climate-resilient infrastructure, such as flood defences or drought-resistant crops, also form part of broader ASP strategies to reduce long-term exposure (Cai et al. 2013).

Furthermore, planned resettlement schemes have been developed to assist communities whose habitats are uninhabitable due to rising sea levels or land degradation. These programmes aim to provide socioeconomic support and

infrastructure development in resettlement areas. However, the long-term success of such interventions remains contingent on institutional capacity, social acceptance, and sustained funding (Nandi et al. 2019). Regional analyses further illustrate communities' compounded vulnerabilities at the intersection of climate stress and socioeconomic fragility. For instance, in the Arab region, climate change has exacerbated challenges related to food insecurity and water scarcity, with projections indicating rising temperatures and more frequent droughts across the region (Wamsler et al. 2020). Over 40% of the region's population is exposed to severe climate risks. In such contexts, development actors such as the United Nations Development Programme (UNDP) have supported the integration of poverty alleviation and climate-action strategies. These initiatives focus on capacity building, climate-resilient livelihoods, and community-based adaptation aims, which align with the broader goals of Sustainable Development Goal 13 (SDG 13) and the 2030 Agenda (Aleksandrova 2020; Hallegatte et al. 2020).

2.2. Trade-Offs and Synergies Between Poverty and Climate Action

The intersection between climate action and poverty alleviation is increasingly recognised as a complex policy domain in which environmental and social objectives can interact in complementary and conflicting ways. Although the urgency of both agendas is uncontested, the approaches used to address them may generate unanticipated consequences, particularly for already disadvantaged populations (Soergel et al. 2021). For instance, policies that reduce carbon emissions, such as carbon taxation or subsidy reform, may increase energy costs. This phenomenon, often referred to as "energy poverty", disproportionately affects low-income households that are already struggling to afford essential energy services such as heating, lighting, and cooking (Yang and Percival 2009; Streimikiene et al. 2020; Aleksandrova 2020).

These challenges highlight the need for climate action to be informed by principles of distributive justice and policy coherence. Without careful planning and inclusive implementation, well-intentioned interventions risk exacerbating existing inequalities. As Cai et al. (2013) argue, mitigation strategies must be accompanied by compensatory mechanisms or targeted support to ensure that vulnerable groups are not further marginalised in transitioning to a low-carbon economy. Thus, identifying and managing policy trade-offs is essential in aligning climate action with poverty-reduction goals.

However, the relationship between climate action and poverty is not solely defined by conflict or trade-offs. A growing body of literature points to numerous

areas of synergy where climate strategies have the potential to yield both environmental and socio-economic benefits. Investments in renewable energy infrastructure, energy-efficient housing, and sustainable transport systems can generate employment and stimulate local economies, particularly in low-income regions (Hallegatte et al. 2018, 2020). The clean-energy sector, in particular, has emerged as a driver of green jobs, offering new labour market opportunities and skill development pathways that may support social mobility for disadvantaged populations (Aleksandrova 2020).

In addition, adaptive strategies that enhance community resilience can contribute directly to poverty reduction. Initiatives such as climate-resilient infrastructure, disaster risk management, and sustainable agricultural techniques serve dual purposes: They mitigate the adverse impacts of climate hazards while strengthening the livelihoods of communities exposed to environmental shocks (Cai et al. 2013). These forms of adaptation are particularly relevant in rural and agricultural settings, where dependence on natural resources is high and adaptive capacity is limited.

The livelihoods of poor and marginalised groups are often closely tied to the natural environment through activities such as small-scale farming, fishing, and pastoralism (Khanal et al. 2021). Climate change threatens these livelihood systems by disrupting ecological stability, altering precipitation patterns, and increasing the frequency of extreme weather events (Wamsler et al. 2020). As a result, environmental degradation threatens food security and income stability and undermines community cohesion and intergenerational well-being. Therefore, the protection and sustainable management of ecosystems assume an important role in poverty-reduction strategies (Streimikiene et al. 2020).

Despite the theoretical potential for synergies, the practical implementation of climate–poverty integration remains constrained by several structural and institutional barriers. The burden of climate impacts is unevenly distributed, with poorer communities often lacking access to adequate infrastructure, social safety nets, or financial capital necessary for adaptation (Soergel et al. 2021; Yang and Percival 2009). These disparities reinforce existing inequalities, limiting the capacity of the most affected populations to respond effectively to climate threats and increasing their susceptibility to deeper cycles of deprivation (Streimikiene et al. 2020).

In view of these dynamics, integrating climate and poverty policies requires an approach that is both context sensitive and equity oriented. Rather than promoting a uniform or prescriptive set of interventions, the literature suggests the importance of aligning climate goals with local development needs, institutional capabilities, and

socio-economic priorities. The case studies examined in this chapter offer insight into the diverse policy mechanisms adopted across different national settings and the extent to which these mechanisms address or overlook social equity concerns.

3. Materials and Methods

This chapter adopts a narrative literature review approach to explore the intersection between climate action and poverty, explicitly identifying the trade-offs and synergies that emerge across diverse national contexts. The objective is to synthesise secondary evidence on how selected countries have designed and implemented climate strategies that align with poverty-reduction goals. It is important to note that this study does not involve collecting original empirical data or fieldwork. Instead, it draws on existing academic and policy literature, using case studies as illustrative examples to conceptualise the climate change–poverty nexus.

The literature search was conducted across three major academic databases, Scopus, Web of Science, and Google Scholar, with the inclusion of English-language publications from 2010 to 2025. The search utilised a combination of keywords, including "climate change", "poverty", "climate action", "climate adaptation", "mitigation", "poverty reduction", and "sustainable development". Boolean operators were used to expand the search results, while backward citation tracking further helped identify foundational and thematically relevant studies. The screening process was guided by the relevance of each source to the overarching research question and the credibility of the publisher or institution.

From an initial pool of approximately 85 documents, a refined selection of 48 sources was included in the final analysis. These comprised 31 peer-reviewed journal articles, 8 book chapters, and 9 grey literature reports. Each source was appraised based on methodological transparency, empirical or theoretical contribution, and alignment with the chapter's focus on the interaction between climate policy and poverty alleviation. Grey literature was only incorporated if produced by reputable organisations known for research credibility, such as the United Nations, the World Bank, the Intergovernmental Panel on Climate Change (IPCC), the International Renewable Energy Agency (IRENA), and other development agencies, including Norad and UNDP.

Five countries were purposively selected to form the case study component of the review, namely, the Bahamas, United Arab Emirates (UAE), Egypt, Norway, and Japan. These countries were chosen to reflect a broad spectrum of regional diversity, levels of economic development, exposure to climate vulnerability, and climate governance frameworks. Each case study illustrates a unique national approach to

integrating climate action with poverty-reduction strategies. A targeted number of documents were reviewed for each country: 7 for the Bahamas, 9 for the UAE, 10 for Egypt, 9 for Norway, and 9 for Japan. These documents include national climate strategies, programme evaluations, international reports, and academic analyses of key policies and initiatives.

Although systematic in its design, this review does not meet the formal requirements of a systematic review or meta-analysis. Instead, it adopts a qualitative, thematic synthesis approach that identifies policy patterns, institutional innovations, and socioeconomic outcomes across different national contexts. The analysis focused on the mechanisms through which climate interventions influence livelihood improvement, income security, social protection, and community resilience. Emphasis was also placed on understanding how policy frameworks have balanced environmental goals with equity considerations, particularly in contexts marked by socioeconomic precarity.

4. Results: Review of Global Climate-Action Initiatives from Five Case Studies

4.1. Bahamas: A Case Study of Climate Action for Small Island Developing States

The Bahamas offers an instructive example of how climate policy can be designed to support both environmental sustainability and poverty reduction. As a Small Island Developing State (SIDS), the Bahamas faces acute vulnerability to climate-change impacts, including sea-level rise, coastal erosion, extreme weather events, and coral-reef degradation (Wamsler et al. 2020). These environmental risks pose significant threats to the country's key economic sectors, mainly tourism and fisheries, and directly affect its population's livelihoods, infrastructure, and well-being (Petzold et al. 2019).

The Bahamas has taken steps to mainstream climate considerations into national development planning. The National Climate Change Policy, as outlined in its First Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC), provides a strategic framework prioritising both adaptation and mitigation (Wamsler et al. 2020; Pathak et al. 2021). Mitigation efforts include a commitment to reduce greenhouse gas emissions by 30% by 2030 relative to a business-as-usual scenario, with 41 targeted actions identified across key sectors (Wamsler et al. 2020). These initiatives are particularly significant given the country's limited contribution to global emissions, and they signal a broader intent to position the Bahamas as a proactive participant in global climate governance (Pathak et al. 2021).

The Climate Change and Carbon Markets Initiatives Bill (2022) further advances these goals by enabling the monetisation of blue carbon through protecting and restoring marine ecosystems such as mangroves and seagrass beds. These ecosystems act as natural carbon sinks and provide crucial ecosystem services that support livelihoods in fisheries, coastal agriculture, and tourism (Petzold et al. 2019). The policy framework introduces economic incentives for conservation, thereby aligning climate mitigation with income generation and local development opportunities.

One of the more concrete illustrations of integrated climate–poverty interventions is the Harbour Island Pilot Project, which tests a climate-resilient development model tailored to a tourism-dependent community. The project combines renewable energy integration, climate-smart agriculture, and sustainable waste management and has reportedly contributed to local employment generation and diversification of income sources (Robinson 2018). Creating green jobs in solar-energy installation, organic farming, and eco-tourism has provided alternative livelihoods in communities that previously relied on low-wage service jobs vulnerable to climate shocks.

Further, national investments in coastal protection, updated building codes, and improved water-management systems have sought to strengthen resilience against drought and flooding. These infrastructural investments aim to safeguard critical public services, particularly in water and sanitation, and ensure the continuity of service delivery to low-income communities during extreme weather events (Wamsler et al. 2020; Pathak et al. 2021). In addition, sustainable practices in agriculture and fisheries have been promoted as part of broader food-security strategies that aim to stabilise rural incomes (Petzold et al. 2019).

Notwithstanding these advances, the Bahamas continues to face substantial challenges in securing the financial and institutional resources necessary to scale up climate-resilient development. Access to innovative climate financing mechanisms, such as carbon markets and multilateral adaptation funds, remains critical. The country's efforts to promote Adaptive Social Protection (ASP) are especially noteworthy. ASP programmes provide time-sensitive financial assistance and employment opportunities during climate shocks, strengthening household resilience and mitigating the risk of impoverishment (Robinson 2018; Pathak et al. 2021). Examples include employment guarantee schemes, cash transfers, and climate-contingent safety nets for vulnerable populations in hazard-prone areas.

Capacity building remains another constraint, particularly regarding technical expertise, public awareness, and institutional readiness. Recognising this, the Bahamas has invested in education and training programmes that promote climate

literacy and build technical capacity at the community and institutional levels (Petzold et al. 2019). These efforts aim to foster local ownership of climate-smart practices in the construction, energy, and natural-resource management sectors. The Bahamas has also demonstrated a strong presence in international climate diplomacy. At the 26th Conference of the Parties (COP26), the Prime Minister of the Bahamas emphasised the disproportionate burden SIDS bears in the climate crisis despite their limited historical responsibility (Robinson 2018). This advocacy reinforces the country's commitment to collective global solutions and frames its domestic efforts as part of a broader call for climate justice.

It is important to emphasise that while the Bahamas provides valuable insights into the potential for integrating climate action and poverty reduction, its case should not fully represent the entire Caribbean or SIDS region. Each country within this category faces distinct socio-economic and environmental challenges shaped by its histories, governance structures, and resource endowments. Nevertheless, the Bahamas' policy architecture, combined with pilot-level interventions and international engagement, offers valuable lessons for similar contexts.

4.2. United Arab Emirates: A Case Study of Climate Action for the Arab States Region

The United Arab Emirates (UAE) presents a valuable example of how a resource-rich, arid country is employing climate policy to address both environmental sustainability and socio-economic development, mainly through efforts to reduce vulnerability and improve livelihoods. While the UAE has positioned itself prominently in international climate diplomacy, primarily through its hosting of the 28th Conference of the Parties (COP28), its domestic and international initiatives warrant a closer examination of poverty alleviation and climate resilience (Krzymowski 2020; Locke et al. 2023).

Although it is not appropriate to treat the UAE as representative of the entire Arab States region, given significant socio-economic, environmental, and political differences among countries, its ambitious renewable energy and climate-resilience strategies provide relevant insights. As a high-income country facing acute environmental risks such as extreme heat, water scarcity, and land degradation, the UAE has invested significantly in mitigation and adaptation mechanisms. These efforts are domestic and directed towards supporting vulnerable communities in lower-income countries (Robinson 2018; Thomas et al. 2020).

One notable example is the "Empowering Lives and Livelihoods: Renewables for Climate Action" initiative, unveiled during COP28. This programme aims to support climate resilience in developing countries by deploying decentralised

renewable energy solutions across critical sectors such as agriculture and healthcare (Krzymowski 2020; Nevitt 2023). These sectors are highly relevant to poverty reduction, given that smallholder farming and informal caregiving dominate rural livelihoods in many low- and middle-income countries (Thomas et al. 2020). Renewable energy interventions in these sectors reduce reliance on costly fossil fuels, improve service delivery (e.g., cold storage for vaccines in health centres), and enhance agricultural productivity contributing to food and energy security and supporting income generation, particularly for women (Robinson 2018; Aleksandrova 2020).

The UAE's investment in clean infrastructure is mainly exemplified by Masdar City, which is designed as a hub for renewable energy and sustainable urban innovation. While Masdar's direct link to poverty reduction is limited within the UAE's socio-economic context, the technological developments and international partnerships emerging from such projects as solar-power installations and waste-to-energy plants have been used to inform international cooperation frameworks, including those led by the International Renewable Energy Agency (IRENA), which is headquartered in Abu Dhabi (Krzymowski 2020; Locke et al. 2023).

Furthermore, the Dubai Green Fund provides concessional financing for clean technology and renewable energy projects, particularly in developing countries, to foster inclusive economic development, energy access, and resilience building (Thomas et al. 2020). This mechanism allows the UAE to contribute to international poverty-alleviation efforts by improving infrastructure in regions that suffer from unreliable energy supplies, which are essential to economic productivity and basic service delivery. On the adaptation front, the UAE's National Climate Adaptation Strategy includes sector-specific actions targeting water security, coastal protection, public health, and agriculture (Nevitt 2023). In an arid country where water scarcity is a defining environmental challenge, investments in desalination technology, water recycling, and conservation initiatives reflect an effort to secure long-term resilience. These investments also have socioeconomic relevance, especially in international contexts through South–South cooperation or bilateral development agreements (Krzymowski 2020). The UAE's Food Security Strategy 2051 also contributes to broader sustainability goals through support for vertical farming, research on climate-resilient crops, and sustainable land-use management. While primarily intended for domestic benefit, knowledge-sharing and partnership programmes associated with this strategy have potential value for knowledge transfer to food-insecure regions (Thomas et al. 2020; Locke et al. 2023).

Regarding global engagement, the UAE plays a strategic role in climate diplomacy and international knowledge exchange. The UAE facilitates dialogue between policymakers, businesses, and researchers to scale up renewable energy adoption and promote inclusive green growth through collaboration with IRENA and platforms such as the World Green Economy Summit. These forums offer avenues for capacity building in low- and middle-income countries, including technical training and financial support for clean-energy adoption (Robinson 2018; Nevitt 2023).

Despite these promising initiatives, several limitations and contradictions remain. The UAE continues to face challenges related to high per-capita energy consumption and carbon emissions, requiring more ambitious domestic energy-efficiency policies and behavioural change interventions (Locke et al. 2023). In addition, while well intentioned, water-intensive projects, such as desert greening, raise sustainability concerns in the context of limited freshwater availability.

It is also important to note that while the UAE's outward investments in climate action contribute to resilience and poverty reduction in partner countries, the domestic applicability of these initiatives to poverty is constrained by the relatively low incidence of extreme poverty within the UAE. Therefore, the relevance of the UAE case study lies primarily in its role as a financial and technological contributor to global climate justice efforts rather than as an internal case of poverty alleviation through climate policy.

4.3. Egypt: A Case Study of Climate Action for Northeast Africa

Egypt, located in North Africa, is highly vulnerable to the adverse effects of climate change despite its arid environment and historically adaptive agricultural systems (Al-Jaber 2023). The country faces a combination of environmental stressors, including rising temperatures, low and unpredictable rainfall, dust storms, and sea-level rise along its Mediterranean coastline (Nandi et al. 2019). Egypt's heavy dependence on the Nile River for agriculture, domestic water supply, and food security heightens its exposure to climate-related water stress (Ead et al. 2022). These climatic pressures are particularly concerning given the country's large rural population, high poverty rates in some governorates, and limited adaptive capacity in under-resourced areas (Al-Jaber 2023; Ibrahim et al. 2021).

The impact of climate change on agriculture is especially critical, as shifts in precipitation and temperature patterns negatively affect crop yields and threaten food security (Al-Jaber 2023). This has far-reaching implications for the country's broader development trajectory, especially for vulnerable communities whose livelihoods depend on farming, fishing, and seasonal labour. Against this backdrop, Egypt has

made considerable policy efforts to integrate climate action with socio-economic development, particularly poverty reduction. A prominent example is Egypt's National Climate Change Strategy 2050, which outlines long-term pathways for achieving climate resilience while promoting inclusive economic development. This strategy includes sectoral priorities such as coastal protection, water-resource management, sustainable energy, and climate-smart agriculture (Ibrahim et al. 2021). These priorities aim to reduce vulnerability among low-income populations by safeguarding livelihoods and strengthening rural infrastructure.

Egypt's issuance of the first sovereign green bond in the Middle East in 2020 represents a noteworthy shift in aligning climate financing with national development objectives (Ibrahim et al. 2021). Proceeds from the bond have been allocated to sustainable transport and water infrastructure, potentially creating new employment opportunities and improving access to essential services in underserved communities (Al-Jaber 2023). These investments target mitigation and adaptation goals and provide an entry point for enhancing economic resilience among disadvantaged groups. The "Green President" initiative, launched in 2014, focuses on scaling up renewable energy sources such as solar and wind. These initiatives aim to increase energy access, particularly in rural areas, and reduce dependence on imported fossil fuels (Nandi et al. 2019). Promoting decentralised energy systems through small-scale solar power installations has contributed to community-based energy security, job creation, and local skill development (Al-Jaber 2023). While data on employment impact remain limited, emerging evidence suggests that renewable energy sectors offer new income-generation avenues in previously marginalised regions.

In parallel, the Decent Life Initiative (Hayah Karima), launched in 2019, provides a multisectoral framework that connects poverty-alleviation efforts with climate resilience (Ead et al. 2022). The initiative targets the most deprived rural areas by improving access to clean water, health services, education, sanitation, and energy. The initiative aims to reduce socio-economic vulnerability to climate risks by integrating infrastructure development with climate-smart practices and enhancing long-term human development outcomes (Ibrahim et al. 2021). Complementing these measures is the 100 million Trees Programme, a large-scale afforestation initiative intended to combat desertification, improve air quality, and enhance biodiversity. The programme's emphasis on rural implementation supports job creation, particularly in land management and urban greening projects (Al-Jaber 2023). Moreover, by improving microclimatic conditions in peri-urban areas, the programme contributes indirectly to health and productivity gains for low-income communities.

Egypt's climate strategy also places a notable emphasis on gender inclusivity. Women are recognised as key actors in household adaptation strategies and are increasingly involved in community decision making. Programmes promoting female entrepreneurship in agriculture, renewable energy, and environmental services are part of national plans to ensure gender-equitable climate resilience (Nandi et al. 2019; Ibrahim et al. 2021). These efforts address longstanding structural inequalities by enhancing women's access to credit, technical training, and formal employment in emerging green sectors. Despite these promising initiatives, challenges remain. A significant constraint is the limited availability of domestic financing, which hampers the scaling of pilot programmes. Egypt's climate agenda relies heavily on international partnerships and development finance institutions to implement national adaptation strategies (Ibrahim et al. 2021). Moreover, there is a need for capacity building at local levels, particularly in translating national policies into community-driven projects. Sustainable outcomes require stronger coordination between government agencies, private sector actors, and civil society organisations to ensure inclusive implementation and accountability.

While Egypt's efforts are commendable, caution must be exercised in interpreting its experience as representative of broader regional dynamics. Although often used as a proxy for the North African or Arab region in international discourse, Egypt's socio-political context, institutional structures, and resource endowments differ markedly from those of neighbouring countries. Generalising findings across regions would require a more extensive and comparative body of literature, which is beyond the scope of this review.

4.4. Norway: A Case Study of Climate Action for Europe

Norway, a high-income country in Northern Europe, has established a strong international reputation for its commitment to environmental sustainability and global development cooperation. While it faces climate-related challenges, including rising temperatures and changing precipitation patterns, Norway's climate policy extends significantly beyond its national borders, mainly through its role in international climate finance (Hlásny et al. 2017; Kvellheim 2017). This case study explores how Norway has utilised various mechanisms to support climate resilience and poverty alleviation in developing countries and the extent to which these initiatives align with the broader themes of this chapter.

One of the central strategies through which Norway contributes to both climate action and poverty reduction is its extensive investment in renewable energy and clean technologies. Domestically, the country's hydroelectric infrastructure provides

nearly all of its electricity, serving as a low-carbon development model (Kvellheim 2017). Internationally, Norway channels funding through bilateral and multilateral programmes to expand clean-energy access in low- and middle-income countries. Through the Norwegian Agency for Development Cooperation (Norad), Norway has supported off-grid solar installations, rural electrification schemes, and sustainable hydropower developments in Sub-Saharan Africa and Southeast Asia (Hlásny et al. 2017). These interventions make energy access a critical enabler of improved health, education, and economic productivity among poor and marginalised populations (Uleberg et al. 2014).

In the multilateral sphere, Norway is a significant donor to the Adaptation Fund and the Green Climate Fund, mechanisms designed to support vulnerable countries in managing climate risks. Adaptation projects funded through Norwegian contributions often focus on food security, water-resource management, and disaster preparedness areas directly affecting poor rural communities (Ads et al. 2023). Notably, at COP28, Norway pledged over 500 million Norwegian Krone (NOK) in new agreements to triple climate finance for adaptation by 2026. These pledges prioritise livelihood protection, particularly in agriculture-dependent regions, and are justified publicly by Norwegian officials through humanitarian responsibility and long-term development impact (Westskog et al. 2022).

Another key channel through which Norway contributes to global poverty-oriented climate action is its support for REDD+ (Reducing Emissions from Deforestation and Forest Degradation). Norway remains one of the largest donors to this initiative, which incentivises forest conservation in developing countries. These funds protect biodiversity and carbon sinks and support the livelihoods of indigenous and forest-dependent communities by recognising and enhancing the value of sustainable land-use practices (Kvellheim 2017). Through such support, Norway indirectly strengthens local capacities to withstand economic and environmental shocks, particularly in rural forested regions of Latin America, Africa, and Southeast Asia (Ads et al. 2023).

Further demonstrating its commitment to resilience, Norway contributes significantly to disaster risk financing and early warning systems. Through the Africa Disaster Risk Financing Programme (ADRiFi) and its grant to the Africa Risk Capacity (ARC), Norway has helped strengthen pre-emptive insurance schemes for African countries facing climate-related catastrophes (Hlásny et al. 2017). The ARC system links early warning data with financial mechanisms, enabling faster and more effective responses to extreme weather events such as droughts and floods. Norway's NOK 70 million grant over three years to ADRiFi supports the integration

of risk analyses into national planning, aiming to reduce humanitarian crises and maintain community stability (Westskog et al. 2022).

In addition to financial instruments, Norway has demonstrated a sustained commitment to strengthening climate information systems and early warning capacity. This includes support for the Climate Risk and Early Warning Systems (CREWS) initiative and the Systematic Observations Financing Facility (SOFF), with combined contributions of NOK 150 million over three years (Westskog et al. 2022). These investments facilitate the generation and dissemination of localised weather data, enabling communities to take proactive measures that protect lives and livelihoods. Such information systems are critical in agriculture-dependent areas, where seasonal variability directly affects food production and income (Kvellheim 2017).

The Clean Technology Fund (CTF), to which Norway is a founding contributor, further reflects its support for low-carbon development pathways in low-income countries. The fund has been instrumental in scaling up renewable energy, energy efficiency, and sustainable transport initiatives, helping governments reduce emissions while creating employment and infrastructure in marginalised regions (Uleberg et al. 2014). These initiatives collectively demonstrate how climate action can contribute to both environmental and developmental outcomes when designed with social co-benefits in mind.

The cumulative impact of these various forms of support is difficult to quantify precisely, but available evidence suggests that Norway's interventions contribute to increased resilience among vulnerable populations. Access to clean energy has enabled extended study hours for school children, increased productivity for small businesses, and reduced health risks from indoor air pollution. Similarly, investment in water management and climate-resilient agriculture has helped stabilise food production in regions exposed to climate variability (Ads et al. 2023).

Nevertheless, it is important to avoid overgeneralisation. While Norway plays an important role in global climate finance, it cannot be considered representative of the entire European region. Its commitment and funding exceed that of many of its regional counterparts, and its policy choices are often shaped by its unique economic structure and political priorities. Therefore, this case should be understood not as a proxy for regional trends but as an illustrative example of how targeted climate finance and international cooperation can be aligned with poverty-reduction goals in vulnerable contexts.

4.5. Japan: A Case Study of Climate Action for Asian Countries

Japan, a highly industrialised nation with a strong reputation for technological advancement, has been a prominent actor in global climate action, particularly within the Asia–Pacific region (Pilli-Sihvola et al. 2015; Kameyama et al. 2016). While it faces its climate vulnerabilities, such as increasing risks from typhoons, floods, and coastal erosion, Japan has implemented a suite of strategies designed not only to mitigate greenhouse gas emissions but also to foster resilience and support poverty reduction, both domestically and through development cooperation (Xie et al. 2018).

A central pillar of Japan's climate strategy is its research and development (R&D) investment in low-carbon technologies. The country has prioritised innovation in renewable energy, particularly solar, wind, and hydrogen, alongside energy-efficient infrastructure (Pilli-Sihvola et al. 2015; Xie et al. 2018). These investments have contributed to reducing dependence on fossil fuels, creating green jobs domestically, and enabling technology transfer to developing countries. However, while Japan has made notable progress, it should be recognised that these efforts represent one national example and cannot be assumed to reflect climate-policy trends across Asia.

The Japan Climate Initiative (JCI) is a key domestic initiative, a network of over 200 stakeholders, including private-sector actors, local governments, research institutions, and civil society organisations (Hasegawa 2020; Mabon and Shih 2021). The JCI promotes collaborative climate action aligned with the Paris Agreement's targets. Its objectives include advocating for net-zero emissions, facilitating stakeholder dialogue, and advancing concrete policy proposals such as introducing international carbon-pricing mechanisms (Xie et al. 2018). These multi-sectoral engagements enhance the coherence of Japan's climate strategy and support inclusive policy processes, although their direct impacts on poverty outcomes require further empirical substantiation.

Regarding climate financing, the Japanese government launched the Green Innovation Fund, which has provided substantial financial and technical support for clean-energy development in lower-income countries (Hasegawa 2020). This support facilitates technology transfer, helping recipient countries to achieve their climate goals while fostering economic opportunities. Similarly, the Innovation for Cool Earth Forum (ICEF) serves as an international platform convened annually by Japan to encourage cooperation between policymakers, researchers, and private-sector actors. The forum showcases technological innovations and promotes global partnerships for decarbonisation (Xie et al. 2018). Although not explicitly designed as poverty-alleviation tools, these platforms contribute indirectly to livelihoods by encouraging investment in sustainable and inclusive technological solutions.

Japan's commitment to climate adaptation and disaster risk reduction (DRR) is particularly relevant for its climate-vulnerable population and international cooperation. The country's National Adaptation Plan (NAP) outlines strategies to manage risks in key sectors such as agriculture, water, and coastal management (Mabon and Shih 2021). Infrastructure improvements, early warning systems, and risk mapping have been prioritised. Furthermore, Japan's DRR expertise developed in response to its exposure to earthquakes and extreme weather is regularly shared with developing countries through technical assistance and training programmes (Pilli-Sihvola et al. 2015). Such efforts build institutional capacity and resilience in partner countries, helping to mitigate the human and economic costs of climate-related disasters.

Another area of Japan's engagement lies in climate-smart agriculture, which supports food security and sustainable rural development. Through bilateral development assistance, Japan promotes drought-resistant crops, efficient irrigation systems, and improved soil management practices in countries facing food insecurity (Kameyama et al. 2016; Hasegawa 2020). These interventions aim to enhance agricultural productivity, reduce vulnerability to climate shocks, and improve the livelihoods of smallholder farmers.

Although Japan's climate policies offer valuable lessons, several challenges remain. For example, the affordability and accessibility of advanced low-carbon technologies remain significant barriers for developing countries. The cost of deployment and the complexity of technology-transfer mechanisms limit the scale and effectiveness of some cooperation efforts (Pilli-Sihvola et al. 2015; Hasegawa 2020). Moreover, while Japan plays an important role in international forums and climate finance, its domestic energy mix still includes significant fossil-fuel use, particularly liquefied natural gas (LNG), indicating room for further improvement in emission reduction (Kameyama et al. 2016).

5. Discussion

This chapter examines how five countries, the Bahamas, the United Arab Emirates (UAE), Egypt, Norway, and Japan, are operationalising the interconnections between climate action and poverty alleviation concerning Sustainable Development Goal 13 (SDG 13). SDG 13 encourages countries to strengthen resilience, integrate climate-change measures into policy and planning, and build institutional and individual capacity to respond to climate risks (United Nations 2015). While each country's approach is shaped by its economic capacity, governance structure, and exposure to climate risk, three major themes emerged from the case studies:

the integration of climate policy with social protection systems, the mobilisation of climate finance to build resilience and livelihoods, and the use of innovation and knowledge exchange as enabling tools. A further cross-cutting insight concerns the importance of policy coherence and contextual sensitivity when linking environmental and poverty-reduction goals.

The findings confirm that aligning climate action with poverty reduction is theoretically possible and already underway in several countries, albeit with varying degrees of integration and success. The Bahamas, for instance, provides a clear example of this alignment through the Harbour Island Pilot Project, which integrates renewable energy infrastructure, sustainable agricultural practices, and solid waste management into one localised programme (Robinson 2018). This initiative is climate resilient, reduces exposure to storm damage and flooding, and is socially inclusive, as it provides alternative livelihood opportunities for residents previously dependent on declining fisheries and tourism industries. This approach addresses SDG 13 targets 13.1 and 13.b by increasing resilience and promoting climate-responsive capacity building in a SIDS context.

Similarly, Egypt's Decent Life Initiative (Hayah Karima) provides a compelling model of how climate adaptation can be embedded in poverty-alleviation programming. By targeting infrastructure development in rural communities ranging from solar-powered water pumps to clean-energy clinics, the initiative promotes inclusive access to essential services while addressing vulnerabilities to heatwaves, water scarcity, and energy poverty (Ead et al. 2022; Ibrahim et al. 2021). These actions respond to the needs of the poorest and most climate-exposed groups, illustrating a grounded operationalisation of SDG 13 within a broader development framework.

By contrast, the UAE and Norway focus less on domestic poverty reduction but act as global enablers through climate finance and knowledge sharing. The UAE's "Renewables for Climate Action" programme supports renewable energy access in agricultural and healthcare sectors across several African and Asian countries. This investment strategy—announced during COP28—is explicitly designed to strengthen climate resilience in developing countries while enhancing productivity and reducing energy poverty (Krzymowski 2020; Nevitt 2023). Norway follows a similar trajectory through its leadership in multilateral climate finance. Its contributions to the Green Climate Fund, Africa Risk Capacity, and REDD+ initiatives aim to enhance food security, early warning systems, and rural livelihoods in low-income settings (Westskog et al. 2022; Ads et al. 2023).

Japan, meanwhile, adopts a dual domestic–international role. Domestically, it invests in low-carbon technologies and disaster preparedness. Internationally,

its platforms, such as the Innovation for Cool Earth Forum (ICEF), foster green technology and sustainable agriculture cooperation in developing countries (Kameyama et al. 2016; Xie et al. 2018). These investments affect agricultural productivity and rural employment, particularly in regions vulnerable to climate-induced food insecurity. Although these diverse strategies offer promising pathways, several countries, especially the Bahamas and Egypt, face implementation barriers related to institutional capacity, limited technical expertise, and inadequate financing (Pathak et al. 2021; Al-Jaber 2023). These constraints threaten the scalability and sustainability of otherwise promising local initiatives.

Integrating Adaptive Social Protection (ASP) mechanisms into climate strategies emerged as a significant, uneven development across the case studies. In the Bahamas, ASP manifests through climate-contingent cash transfers, temporary job schemes, and social safety nets activated during extreme weather events (Robinson 2018). These mechanisms support household coping capacity while addressing systemic vulnerabilities associated with recurring climate shocks.

In Egypt, the Decent Life Initiative's integration of clean-energy provision, job creation, and service expansion in vulnerable rural communities represents an embedded ASP approach. Notably, the initiative includes employment-based public works and social housing that reduce carbon emissions and provide economic stability to at-risk groups (Ibrahim et al. 2021).

These approaches reflect operational examples of SDG 13.1 and 13.b, which call for resilience strengthening and support for the least-developed countries. However, findings indicate that ASP remains limited in scale, with an insufficient inclusion of informal sector workers, a group that forms most of the workforce in many climate-exposed regions (Aleksandrova 2020; Soergel et al. 2021). The lack of formal registration, limited insurance markets, and insufficient state capacity to deliver responsive benefits hinder the extension of ASP coverage.

All five countries demonstrate how climate finance can catalyse green growth and poverty reduction, yet access, equity, and utilisation remain critical challenges. Egypt's green bonds, issued in 2020, represent a proactive effort to fund public climate-resilient infrastructure while stimulating job creation and environmental sustainability (Ibrahim et al. 2021). Similarly, the UAE's Dubai Green Fund channels private investment into renewable energy and green building projects, with downstream benefits for energy access and employment (Locke et al. 2023).

Norway emerges as a leader in international climate financing, contributing to funds focused on early warning systems, food-system resilience, and post-disaster

recovery in fragile contexts (Ads et al. 2023). These investments directly support SDG 13's commitment to enhance developing countries' adaptive capacity.

However, access to finance is constrained mainly for countries such as the Bahamas and Egypt by complex application processes, low national credit ratings, and limited administrative capacity (Petzold et al. 2019; Al-Jaber 2023). Even when funding is secured, projects often struggle with timely implementation and monitoring of socio-economic outcomes. The broader lesson here is that finance must be pro-poor by reaching vulnerable communities and investing in local infrastructure, skills, and service delivery to generate sustained benefits.

Technological innovation and knowledge transfer are essential in linking climate goals to social development. In this regard, Japan and the UAE stand out. Japan has heavily invested in climate-smart agriculture, early warning systems, and disaster-risk-reduction tools, which it shares with developing countries through technical assistance and training programmes (Mabon and Shih 2021; Kameyama et al. 2016). These technologies improve food security, reduce exposure to hazards, and enhance local institutional capacity.

The UAE complements this approach through strategic investment in solar irrigation, clean cooking solutions, and off-grid renewable energy, particularly in African and Asian rural communities (Krzymowski 2020). These interventions directly support the SDG 13.3 target of improving education and awareness about climate risks and adaptation strategies.

Nevertheless, challenges remain in adapting technologies to local needs. High costs, lack of technical literacy, and poor infrastructure frequently limit the sustainability of innovation-based programmes (Pilli-Sihvola et al. 2015; Hasegawa 2020). Egypt's case illustrates this tension: while solar-powered health clinics have been piloted successfully, scaling such efforts across underserved regions is financially and technically demanding (Ibrahim et al. 2021).

Also, a key finding across the case studies is that effective integration of climate action and poverty reduction requires context-specific strategies and strong policy coherence. One-size-fits-all approaches fail to address each country's unique vulnerabilities, institutional capacities, and socio-political realities. For instance, although the UAE plays a critical role in global climate finance, it cannot be assumed to represent broader Middle Eastern or Arab states (Locke et al. 2023). Likewise, Norway's international leadership in climate finance should not obscure the diversity of climate financing approaches within Europe (Kvellheim 2017). Even among SIDS, the Bahamas has a distinctive governance structure and development trajectory that affects its climate response capacity.

Hence, advancing SDG 13 alongside poverty-reduction goals requires tailored national strategies, robust inter-ministerial coordination, and sustained local engagement. Countries must move beyond mitigation-centric frameworks and incorporate vulnerability mapping, social protection, livelihood diversification, and inclusive financing into their national climate-action plans (Hallegatte et al. 2018; Soergel et al. 2021).

6. Conclusions

The findings of this chapter emphasise the intricate and often multidirectional relationship between climate action and poverty reduction. Drawing on the experiences of five diverse national contexts, the Bahamas, Japan, Norway, Egypt, and the United Arab Emirates, this review illustrates how climate policies can serve environmental and socio-economic objectives when designed with equity, inclusiveness, and policy coherence. However, it also reveals that achieving such dual outcomes is neither automatic nor universally guaranteed.

While each case study provided specific examples of successful climate–poverty integration, such as Egypt's Decent Life Initiative, the UAE's renewable energy investments in developing countries, or Japan's focus on climate-smart agriculture, structural and contextual factors often shape the extent and durability of such successes. In particular, the chapter highlights the importance of adaptive social protection, sustainable livelihoods, technological innovation, and decentralised governance as enabling conditions for reducing poverty through climate action.

These insights contribute to the growing body of literature supporting the alignment of national and international efforts with Sustainable Development Goal 13, which calls for urgent climate action and increased resilience to climate-related hazards. The cases reviewed demonstrate progress on key SDG 13 targets, including integrating climate-change measures into national policies and improving capacity for effective climate planning and management in vulnerable regions. Moreover, the chapter reinforces that achieving SDG 13 must go beyond environmental metrics to include inclusive development outcomes benefiting low-income populations.

Despite these promising examples, limitations persist. Many of the climate interventions studied remain at the pilot or project level, often constrained by limited financing, weak institutional capacity, and insufficient integration with broader development frameworks. Furthermore, while international cooperation plays a vital role mainly through climate finance and technology transfer, more effort is required to ensure that such support is locally grounded and reaches the most vulnerable populations.

In light of these findings, this chapter advocates for a more deliberate framing of climate policies through a poverty reduction lens. Policymakers and practitioners should prioritise environmental and social co-benefit interventions, especially in agriculture, energy, and water sectors. In doing so, climate action can contribute to environmental goals and serve as a catalyst for inclusive and sustainable development.

Future research should examine the long-term effectiveness and scalability of integrated climate–poverty strategies, especially in low-income and fragile contexts. As climate change's impacts become increasingly severe and unevenly distributed, it is imperative that both global and national actors adopt holistic, equity-driven approaches to climate governance that truly leave no one behind.

A limitation of the study is due to its focus on a single country within the selected regions. Because many countries react differently to climate change, while the different countries within each region are on different scales of poverty, it may be difficult to provide solutions on climate-action strategies based on a few selected countries for other countries to adopt, particularly the least-developed countries, who may not have the infrastructure to support some of these strategies. As a result, future research on this subject matter may explore more countries in each region, particularly the least-developed countries, to establish more robust findings on the climate change–poverty nexus for the poor and most vulnerable countries.

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The Adoption and Scaling of Stress-Tolerant Rice Varieties: A Sustainable Climate Adaptation Strategy for Smallholders

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1. Introduction

Agriculture is important in securing livelihoods and advancing a country's economic prosperity. It is the largest sector known to experience a significant impact from climate change and variability because of its size and sensitivity (Malhi et al. 2021). Climate change not only threatens national food security but also affects farmers' welfare, causing suffering, especially among smallholder farmers (Tofu et al. 2022). Smallholder farmers are susceptible to the effects of climate change because they have limited adaptive capacity, as their social, human, physical, natural, and financial resources are compromised. Hence, climate change and variability are viewed as a threat to their agricultural production.

Globally, an estimated 600 million smallholder farmers cultivate less than 2 ha of land each and contribute to 28–31 percent of total crop production and 30–34 percent of food supply from 24 percent of the gross agricultural area (World Economic Forum 2022), even though many of them are impoverished, face food insecurity, and live in extremely precarious conditions (Harvey et al. 2014). India houses the majority of small and marginal farmers, accounting for 86 percent of the total number and 47 percent of the overall cultivable land (Jha et al. 2022). Assam is an agrarian state in India, with agriculture accounting for 37 percent of the total geographical area and 53 percent of the working population (Baruah et al. 2021), with the majority of farmers in the marginal (62.2 percent) and small (20.9 percent) categories (IRRI 2023). Rice, as a staple food, is a vital crop for the state's sizeable population. However, the rice-based cropping systems in this region exhibit low productivity, mostly because of the prevailing biotic and abiotic stresses associated with rainfed cultivation.

The Green Revolution had a marked influence on agricultural production systems based on irrigation but not on rainfed systems prone to floods and drought, thus excluding the smallholders who face food insecurity and poverty (Abraham and Pingali 2020). Mostly rainfed farmers belong to small and marginal groups, and

are extremely vulnerable to the impacts of climate change due to their reliance on natural resources that are sensitive to climatic conditions. Additionally, they often cultivate areas with limited agricultural potential and lack the necessary technical and financial assistance to invest in more resilient farming practices (Shikwambana et al. 2022). There is rising evidence that smallholder farmers are susceptible to the effects of climate change (Tang and Atakelty 2020), and more focus is laid on ensuring food security in the face of climate change (Vermeulen et al. 2012; Lipper et al. 2014). However, there is still a need for increased productivity as well as adaptability to the hazards associated with climate change. As a result, it is critical to implement a suitable adaptation strategy to mitigate this threat and boost farmers' income.

In this situation, the improvement in abiotic stress tolerance can enhance the production, productivity, and overall profitability of the system. The adoption of stress-tolerant rice varieties (STRVs) could be one of the most effective risk adaptation approaches for overcoming climate change challenges (Khanam 2021). By offering resilience to climate change, STRVs can be one of the most pragmatic approaches in stress-prone locations where smallholders are highly reliant on paddy cultivation (Veettil et al. 2021). Integrating stress tolerance into high-yielding varieties has proven to be a very efficient method in the development of promising varieties for stress-prone conditions. These accomplishments raise the possibility that developing and disseminating adaptive germplasm will help address the issue of climate change, and the widespread adoption of climate-resilient high-yielding rice varieties can help achieve this. These adaptive germplasms need to be supported by dissemination strategies for widespread adoption.

Rice plays a vital role in ensuring food availability and income security for both rural and urban populations in Assam. Smallholder farmers are at the forefront of rice production systems, with more than 80 percent of the total rice production in Assam attributed to them. In Assam, the soil, topography, rainfall, and climate are very conducive to paddy cultivation. In the years of 2020–2021, the total rice production was 5.10 MT with an average yield of 2187 (kg/ha). In the same year, the national rice productivity was 2705 kg/ha, which was 11 percent higher than that in Assam. The year-wise seed production details from 2015 to 2016 are given in Table 1. Though rice commands the largest cultivable area and is a priority for the farmers and the state agricultural department, there has been a steady decline in the rice-cultivated area in the state due to decrease autumn (Ahu) and summer (*Boro*) rice area. The yield of rice also fluctuated between 2015–2016 and 2020–2021 for all the seasons of cultivation (DES 2022).

Table 1. Area, production, and productivity of rice crop during 2015–2016 to 2020–2021.

Year	Area (million ha)	Yield (kg/ha)	Assam Production (million tonnes)	India Production (million tonnes)
2015–2016	24.85	2062	5.22	104.41
2016–2017	24.67	2059	5.13	109.70
2017–2018	24.34	2150	4.73	112.76
2018–2019	24.26	2176	5.28	116.48
2019–2020	24.01	2099	5.22	118.43
2020–2021	23.60	2187	5.10	122.27
2021–2022	23.53	1886	4.38	129.00
2022–2023	23.08	2652	6.04	135.75

Source: Authors' compilation based on data from DES (2020, 2022, 2023).

Winter (*Sali*) rice dominates rice production in the state. In the case of the yield, summer (*Boro*) rice has a higher productivity than the other two seasons and is witnessing a higher growth rate. The cost of production of wet season (*Sali*) rice is low, and so is the productivity, largely because of the inadequate usage of inputs due to the fear of crop damage/failure by floods, and low or no cost incurred on irrigation. Localized drought-like situations and severe floods that the state often experiences during the peak *Sali* season results in low yields during winter season. The low productivity of rice and other crops due to low seed and varietal replacement rates, poor crop management, imbalances in agriculture development across districts, post-harvest losses, and inadequate processing facilities are some of the critical problems that the agriculture sector in Assam faces today.

The Agriculture Department and the Agricultural University of Assam are focusing on raising the productivity of rice by distributing seeds of high-yielding and stress-tolerant rice varieties among the farmers free of cost. The International Rice Research Institute (IRRI) and Assam Agribusiness and Rural Transformation Project (APART) are also collaborating to promote climate-resilient rice varieties and premium-quality rice (PQR) varieties in the region. Assam's seed sector, in general, remains underdeveloped despite the availability of a myriad of notified varieties that have a high potential for productivity enhancement. The seed sector in the entire North East Region (NER), including Assam, is characterized by poor institutional arrangements and linkages.

2. Major Abiotic Stresses in Assam

Climate change threatens sustainable agriculture with its rapid and unpredictable consequences, making it more challenging for agricultural researchers and farmers. Climate change has been increasingly visible in terms of changes in temperature, precipitation, retreating ice caps and glaciers, sea level rise, atmospheric circulation patterns, and ecosystems. The effects are not just limited to increasing temperatures but also the increasing frequency of extreme weather events, such as heat waves, cold waves, droughts, and floods. Climate change has led to reduced precipitation rates in Arunachal Pradesh, Manipur, Mizoram, and portions of Assam state. Meghalaya and the western region of Assam have experienced an increase in rainfall over the past two decades (Halder and Yaseen 2024). According to the India Meteorological Department (IMD), the temperature in the state is expected to rise by 1.7 to 2.0 °C between 2021 and 2050 due to an increase in the frequency of heavy rain events (ASSAPCC 2015). Assam is an important rice belt in India and the diversified agro-climatic zones of Assam offer great potential for the cultivation of rice. However, the state is home to a mega-network of rivers comprising 48 major and 128 small rivers, which are responsible for the annual floods, resulting in an average annual loss of INR 200 crores to the state (Sarma et al. 2022). The major abiotic stresses—soil acidity, iron toxicity, aluminum toxicity, low light intensity, low temperature, flooding, and moisture deficit stress—have factored into a lower productivity of rice (Kumar et al. 2017). The numerous abiotic stress factors that could affect plants are shown in Figure 1. Some of the adverse conditions are discussed below.

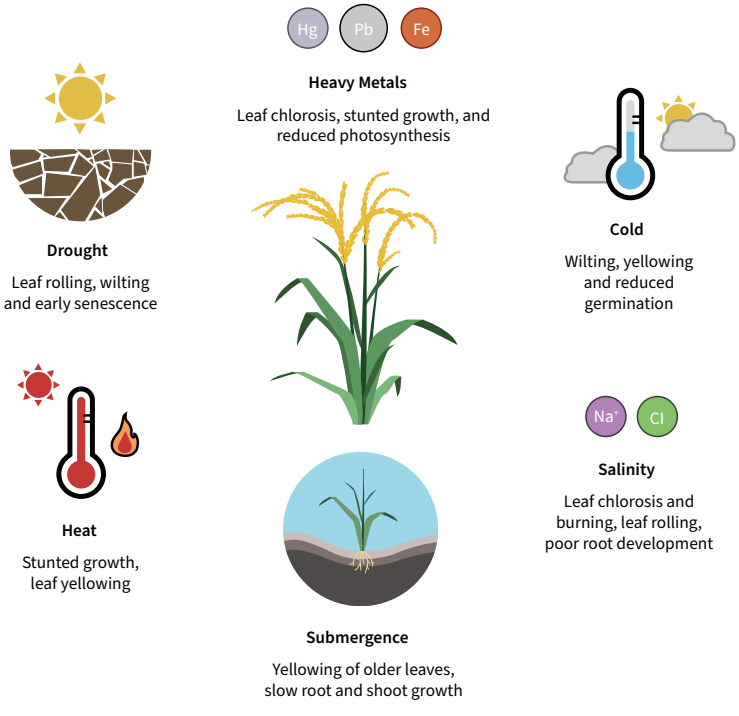


Figure 1. Major abiotic stresses in rice and their effects. Source: Authors' compilation based on data from Sarma et al. (2023).

2.1. Submergence Stress

Submergence is regarded as the third most significant constraint for higher productivity in eastern India among the 42 biotic and abiotic stresses impacting rice production (Sarkar et al. 2014). Excessive flooding contributes significantly to the poverty and vulnerability of marginalized communities. In India, approximately 33 percent of the cultivable area is flood-prone (Ranuzzi and Srivastava 2012). Assam is one of the major flood-affected states in India due to its extensive river network. Each year during the monsoon period, the Brahmaputra and Barak rivers, together with over 50 tributaries, cause devastating floods that not only destroy lives and valuable crops but also lead to riverbank erosion and drainage congestion. The flood problem in Assam differs from other states due to its distinctive characteristics in terms of the scale and duration of floods, as well as the severity of erosion. The frequency of floods has increased in the recent past due to climate change (Krishnan et al. 2020). Around 0.5 Mha of rice areas comes under chronically flood-prone, i.e., 16 percent of the total submerged rice crop area in India (Kannan et al. 2017; Sinha

et al. 2019). Flooding occurs annually in multiple phases in the state and causes widespread devastation. Floods, flash floods, river-bank erosion, and sand casting are the most frequent water-induced hazards in Assam, more particularly in the Lakhimpur and Dhemaji districts (Gogoi et al. 2023).

Rice is a semi-aquatic crop and tolerates partial submergence better than any other crop but dies within a few days when completely submerged. Rice is mainly cultivated in the *kharif* season in Assam when there are frequent flood incidences. Therefore, some farmers in flood-prone areas, particularly in lowland areas, keep their cultivable land fallow (Singh et al. 2016). This results in lower income, food insecurity, and an increased vulnerability of farmers who rely heavily on agriculture (Somanathan and Somanathan 2009). The regular occurrence of floods has been found to negatively impact farm income, discouraging farmers' willingness to experiment with new technologies, such as the adoption of new varieties (Dar et al. 2017). Nevertheless, the occurrence of excessive flooding can lead to various environmental challenges that are associated with either partial or complete submergence. It was concluded from a study that varieties and submergence duration had a significant influence on the morphological characteristics of rice in the early vegetative stage (Sultana et al. 2018). Submergence stress can affect rice crops in different stages from seed germination to seed harvesting. Soil waterlogging normally takes place in the case of rainfall after the sowing of seeds, particularly where the lands are not properly leveled, resulting in slow seed germination, and uneven and delayed seedling establishment. Flash flooding can occur due to heavy rains or the overflowing of rivers and streams for a short duration of 1–2 weeks and results in the complete submergence of plants (Vergara et al. 2014). Lands in low-lying land areas, and near streams and rivers are generally affected by such flash flooding. Depending on climatic conditions, flash flooding can occur repeatedly in a growing season, damaging rice cultivation (Panda and Baril 2021). In stagnant flooding, the water depth ranges from 25 to 50 cm and some parts of the shoot are normally seen over the flood water, and in deep-water flooding, water stagnation continues to remain for a longer time.

2.2. Drought Stress

Drought is the most serious threat to agricultural food production in the face of climate change. Drought intensity/severity is highly complex and is determined by a variety of factors such as rainfall frequency, evaporation, and soil moisture. Terminal drought occurs when a prolonged lack of water causes plant death, whereas intermittent drought occurs when a lack of water for a brief period causes improper

growth. The vegetative growth and grain yield of rice are severely reduced when water is scarce. Drought stress frequently causes reductions in grain size, grain weight, and seed-setting rate. Several drought-tolerant varieties have been developed in the last decade and have been widely adopted (Das et al. 2022). Northeast India (NEI), known for its high rainfall around the globe (Choudhury et al. 2019), has traditionally been regarded as one of the least drought-prone regions in India (Thomte et al. 2022). The occurrence of unprecedented droughts in the years 2006 and 2009 had a devastating effect on the predominantly rainfed agriculture in the state, resulting in significant implications for the livelihoods of several farmers in the region (Das et al. 2009; Parida and Oinam 2015). The probability of drought in NEI between 2000 and 2014 was twice as high as in Western India, speaking of its vulnerability to drought (Parida and Oinam 2015).

Since the 1970s, there has been a discernible increase in annual and seasonal temperatures in the NEI region, except for the spring/pre-monsoon season. Notably, the warming trend has been most pronounced during the post-monsoon season (Dash et al. 2012; Kumar and Dimri 2018). Along with an increase in mean annual temperature and rainfall (Dash et al. 2012), there is also a projected rise in the frequency of extreme monthly minimum and maximum temperatures (Bidyabati et al. 2018). The seasonal variations in anticipated rainfall begin with winter rainfall. Although this humid region is classified as experiencing a rare drought event with a frequency of once every 15 years. Assam (Bongaigaon, Cachar, Dhubri, Goalpara, Golaghat, Kailakandi, Jorhat, Kanpur, Karbi-Anglong, Kokrajhar, Lakhimpur, Morigaon, Nagoan, Nalbari, Sivasagar, Sonitpur) experienced drought consecutively during 2005 and 2006. In the subsequent years of 2009 to 2011, approximately 10–14 districts of Assam had recurrent droughts, indicating a regular pattern of droughts in the recent decade. Insufficient precipitation, with a decrease of 9 percent, during the *kharif* season of 2014 resulted in a significant drought that impacted approximately 12–14 districts within the state. This drought had a detrimental effect on crop output.

In recent years, there has been a notable increase in the occurrence of periodic dry spells during the *Sali* season, which has emerged as a serious weather concern, causing widespread crop damage. Generally, long-duration rice varieties transplanted in lowland fields were not affected by midseason or terminal dry spells (Neog et al. 2020). However, if sowing is delayed beyond the third week of June due to monsoon delay, these varieties suffer from low-temperature stress (below 20 °C) during anthesis, resulting in grain yield reduction. Thus, developing and deploying drought-tolerant varieties are essential to maintaining *Sali* rice production.

2.3. Cold Stress

Cold stress in the seedling stage is a major constraint in *Boro* rice production. *Boro* rice cultivation is originated as a means of livelihood in regions prone to flooding, where it was cultivated in the winter season by utilizing stored water in the lowlands. Typically, *Boro* rice cultivation occurs in swampy, low-lying, or medium-sized lands, accompanied by supplementary irrigation from November to May. The *Boro* rice system utilizes the residual moisture following the *kharif* rice harvest. This rice has traditionally been grown in the river basin deltas of eastern India, including Bihar, West Bengal, Assam, and sections of Odisha. However, the main environmental factor limiting its cultivation is cold stress. Cold stress has an adverse effect on the physiology of rice plants. These physiological changes lead to visual/morphological alterations. Chilling stress symptoms occur in germination stage and proceed further until maturity. Germination or seed emergence is delayed or reduced under cold stress (Rehman and Tanti 2022). However, traditional *Boro* rice varieties are cold-tolerant in the early vegetative stage along with a combination of desired traits such as early maturity and high tillering ability. However, such varieties also possess undesired characteristics like short panicle, bold grain, red kernel, presence of awn, weak culm, tall plant stature, non-synchronous maturity, and poor grain yield (2–3 t/ha). These characteristics make them unfit for intensive cultivation (Bhakta et al. 2021). Low temperatures during the seedling stage result in poor germination, stunted seedling growth, and seedling mortality, all of which have a direct impact on yield (Pathak et al. 2003). Manual uprooting and transplanting are also hampered by stunted seedling growth. As seedlings are raised during the cold months of November and December, cold tolerance in the seedling stage is a primary requirement of *Boro* cultivars (Tiwari et al. 2009). Moreover, rice is very sensitive to low temperatures, and due to long cold spells, the duration of panicle initiation and maturity period also increases. Boro rice, being a winter crop, can escape insect infestation in the seedling stage but faces low temperatures during seedling and vegetative growth (Devi et al. 2023). Therefore, the growth and development of the plant are adversely affected. It is challenging for the farmers to raise rice seedlings due to low night temperatures in the nursery beds. Although low temperature does not prevent germination, it leads to delayed seedling emergence (Haj Sghaier et al. 2023). The performance of rice seeds during germination is important for fast growth and for obtaining a uniform crop stand. Cold tolerance in the seedling stage enables plants to produce more than susceptible genotypes, as a higher survival percent of genotypes in the seedling stage ensures optimum plant population in the field (Kumari and Jaiswal 2017).

2.4. Heat Stress

One of the most devastating environmental stresses that crop plants face is high temperatures; temperatures between 35 and 40 °C are referred to as heat stress (Hasanuzzaman et al. 2013). High temperature is a problem in rice production throughout the tropical areas of Asia. If it exceeds the critical temperature, it affects the normal physiological activities of rice in different growth stages. As a result, growth stunts, pollen sterility, and low spikelet fertility occur, and the yield reduces drastically (Masuduzzaman et al. 2016). The high-temperature stress condition occurs when the soil temperature rises due to an increase in air temperature, followed by a decline in soil moisture. Declining soil moisture further reduces the absorption of photosynthetically active radiation, impairs radiation use efficiency, and decreases the harvest index (Fahad et al. 2017). Thus, heat stress has been identified as one of the most significant challenges to achieving optimal crop productivity worldwide. The delayed commencement of the monsoon has resulted in a postponement of the sowing of *Sali* rice, subsequently leading to a delay in harvesting and ultimately affecting the timing of *Boro* rice sowing. As a result, *Boro* rice is subjected to terminal heat stress in later stages, resulting in a decrease in crop yield.

In addition to these abiotic stresses, losing the crop season is one of the factors that influence farmers' livelihoods and system sustainability. Long-duration paddy varieties prevent farmers from sowing a second crop soon after harvest, which limits their ability to increase cropping intensity. Therefore, in this situation, a medium-duration variety of 120–125 days should be preferred to minimize the pre-harvest sprouting of *Boro* rice and to have successful thermo-sensitive crops like mustard in time after the harvest of *Sali* rice. In addition, short-duration varieties provide an extended window between the harvesting of *kharif* paddy and sowing of subsequent *rabi* crop, thereby giving sufficient time (20–25 days) to the rice farmers for field preparation of the *rabi* crop (Bhagawati et al. 2022).

3. Strengthening Seed Systems and the Adoption of High-Yielding Stress-Tolerant Rice Varieties

The adoption and diffusion of agricultural technologies are expected to help make production systems more protective, productive, profitable, and sustainable. The adoption of new varieties with better seeds is the most economical way for smallholder farmers to increase yields and profitability, as they do not have to spend more on external inputs. The most effective strategy to address the issue of abiotic stresses is to develop, disseminate, and adopt stress-tolerant high-yielding rice varieties with higher quality (Singh et al. 2013). High-yielding STRVs could enhance

and maintain rice productivity in unfavorable environments with stress-prone areas. These STRVs have allowed farmers to cultivate the crop in regions where it was previously abandoned due to the frequent occurrence of abiotic stresses (Mackill et al. 2012). In Assam, the main abiotic stresses that farmers face are submergence and drought. In addition to these stresses, another limiting factor is the cultivation of long-duration varieties. One of the major reasons for low yield is that 88 percent of the rice grown in Assam is under rainfed conditions with unpredictable and uneven distributions of rainfall. The frequency of floods has increased in the recent past due to climate change (Krishnan et al. 2020). Around 0.5 Mha of the rice area is chronically flood-prone, i.e., 16 percent of the total submerged rice crop area in India (Kannan et al. 2017; Sinha et al. 2019). Flooding occurs annually in multiple phases in the state and causes widespread devastation. For instance, the most recent estimates show that flood-associated agricultural losses are USD 18.3 million in the state (DES 2020). Flood- or submergence-tolerant rice varieties can save on the expenses associated with re-transplanting in the case of submergence and can further realize additional yields with improved agronomic management practices (Mamun et al. 2017). In rainfed areas, upon failure of rain or a long spell between two rains, intermittent drought stress can occur in the seedling, vegetative, and reproductive stages of the rice, depending upon the rainfall pattern and distribution. Drought is more complex than other abiotic stresses. It can occur at any point during the season and for any length of time, causing heavy crop losses. Cultivating crop varieties tolerant to climate stress is the most cited adaptation measure. To resolve the concerns, various STRVs have been distributed throughout Assam under the APART project. Ranjit-Sub1, Bahadur-Sub1, Swarna-Sub1, and BINA Dhan11 are varieties of rice that can tolerate submergence. DRR Dhan 44 and DRR Dhan 42 are the drought-tolerant varieties disseminated in Assam. In addition, medium-duration and short-duration high-yielding rice varieties are also promoted in Assam to increase the cropping intensity in the state. Since the use of STRVs alone cannot fully address the issues due to climate stress, land allocation to different varieties also need to be considered. Farmers often use multiple varieties of desirable traits in the same season. The varietal traits are related to consumption preferences (such as cooking quality and taste), production (such as early maturing, high-yield potential, tolerance to stress, e.g., pests and diseases, drought, and submergence), and market-related attributes (such as better processing quality and plant and grain size) (Mehar et al. 2022). The details of varieties and salient features are elaborated in Table 2 and the subsequent evidence unequivocally demonstrates the superior performance of STRVs compared to HYVs presented in Table 3.

Table 2. Details of stress tolerance and other high-yielding varieties and their salient features.

Varieties	Duration (days)	Sowing Time	Seasons	Yield (t/ha)	Salient Features
Drought-tolerant short-duration rice varieties					
DRR Dhan 44	115–120	Dec/Jan	Boro	4.5–5	Rainfed/irrigated uplands/high yielders with less water
DRR Dhan 42	120–125	Dec/Jan	Boro	4.5–5	
BINA Dhan 17	115–120	Dec/Jan	Boro/early Ahu	5–5.5	
Submergence-tolerant short/medium-duration varieties					
BINA Dhan 11	120–125	July	Sali/Boro	5.5–6	Photo-insensitive, submergence-tolerant
AAU-TTB Dhan 40 (Dholi)	130–135	July	Sali	5.5–6	
Submergence-tolerant long-duration varieties					
Ranjit-Sub1	150–155	June	Sali	5.5–6	Can tolerate up to 14 days of complete inundation
Bahadur-Sub1	150–155	June	Sali	5.5–6	
Swarna-Sub1	145–150	June	Sali	5.5–6	
Multiple-stress (submergence and drought)-tolerant long/short-duration varieties					
CR Dhan 801	140–145	June	Sali	5.5–6	Shallow lowland and drought-prone areas, submergence-tolerant
CR Dhan 802	140–145	June	Sali	5.5–6	
DRR Dhan 50	115–120	July and Dec/Jan	Sali, Boro/early Ahu	4.5–5	Tolerant to submergence at seedling, and drought in reproductive stage
Premium-quality (aromatic) rice varieties					
Keteki Joha	150–160	June	Sali	3.5–4	Small grain, highly aromatic
Kola Joha	150–160	June	Sali	2.5–3	
CR Sugandh Dhan 909	140–145	June	Sali	4.5–5	Aromatic
Biofortified short/medium-duration specialty rice varieties					
CR Dhan 310	115–120	July/Jan	Sali/Boro	5–5.5	Protein-rich
CR Dhan 311	120–125	July/Jan	Sali/Boro	5–5.5	Protein- and zinc-rich
CR Dhan 315	125–135	June	Sali	4.5–5	Zinc-rich

Source: Authors' compilation based on data from RCSKB (n.d.).

Table 3. Performance of submergence-tolerant rice varieties over HYVs.

Sr. No.	Location	Name of STRV	Percent Yield Gain over Local Check	Reference
1.	Orissa, India	Swarna-Sub1	45	Dar et al. (2013)
2.	Northwest Bangladesh	Submergence-tolerant (Sub1) rice varieties	8	Bairagi et al. (2021)
3.	Bangladesh	BRRI Dhan51 (Swarna-Sub1)	14.1	Nayak et al. (2022b)
4.	Bangladesh	BRRI Dhan52 (BR11-Sub1)	10.2	Nayak et al. (2022b)
5.	Assam, Odisha, and West Bengal	Swarna-Sub1	19.0	Raghu et al. (2022)
6.	Assam	BINA Dhan 11	26.3	Nayak et al. (2022a)

Source: Authors' compilation based on data from Dar et al. (2013), Bairagi et al. (2021), Nayak et al. (2022b), Nayak et al. (2022b), Raghu et al. (2022), and Nayak et al. (2022a).

Breeder Seed Indent of Rice Varieties in Assam

New rice genotypes are developed continuously with an improvement in one or more traits of economic importance through breeding innovations at the National Agricultural Research Institutes (NARIs), State Agricultural Universities (SAUs), and private seed industries (Prasad et al. 2022). Breeder seed (BS) multiplication takes place at SAUs and ICAR research stations under the observation of the Government of India (GOI). Foundation seeds are multiplied at the state level by state seed corporations (SSCs), the National Seed Corporation (NSC), and licensed private companies, which order and receive breeder seed allocations through a structured demand planning and production process. Therefore, sustainable access to EGS (breeder and foundation seed) is important for the efficient supply of quality-certified and/or quality-declared seeds of improved high-performing crop varieties (Ojiewo et al. 2018).

Breeder and foundation seeds are multiplied by SAU, ASCL, FPCs, and private seed companies in Assam. From 2021 to 2023, 576.5 quintals of breeder seeds of 25 varieties (STRVs and other HYV varieties) were indented from Assam (Figure 2).

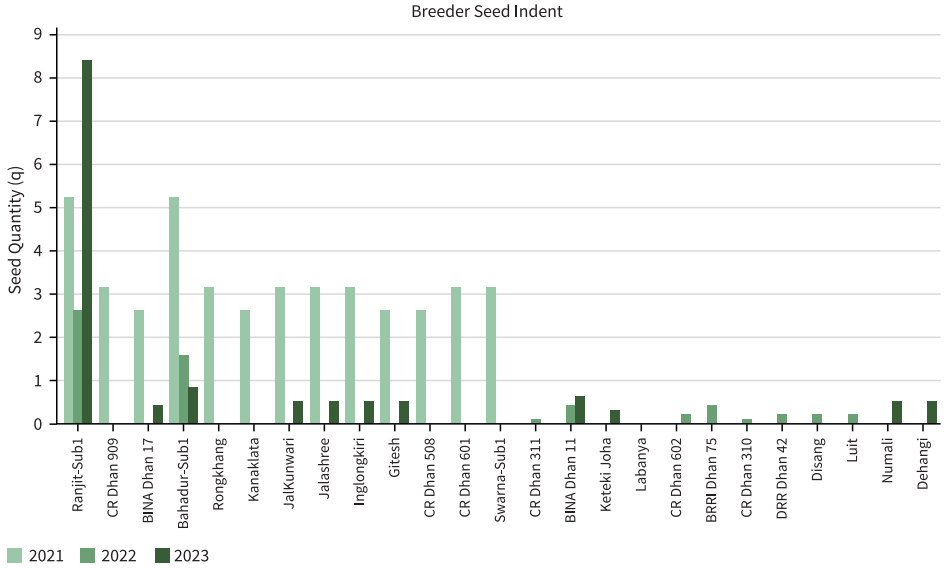


Figure 2. Breeder seed demand (q) for Assam (3-year, 2021–2022–2023). Source: Authors' compilation based on data from Seednet India Portal (n.d.).

The possible underlying reason for the rapid spread of STRVs in Assam may be the prevailing popularity of both Ranjit and Bahadur for three long decades since 1994, with Ranjit covering the largest area. Therefore, there was no hurdle in the transition/switchover of Ranjit and Bahadur to their Sub 1 versions (released in 2018) with similar characteristics. This can be substantiated by a varietal adoption study in Nepal where the adoption of rice varieties released in the previous 15 years (2005/06–2022) was low except for STRV Sawa Masuli-Sub1, which was adopted in 16 percent of the study area more than a decade after its official recommendation due to the advantage of exhibiting similar grain characteristics to the established variety Sawa Masuli, which millers could easily replace with the new variety (Joshi et al. 2023). However, the STRV adoption in Assam has witnessed a much faster pace covering 19 percent of the total rice area in 5 years, as compared to the 16 percent area covered in 10 years in Nepal. In addition, in Assam, the short-duration high-yielding submergence-tolerant rice variety BINA Dhan11, suited to both *Sali* and *Boro* seasons and best fit for post-flood situations, was widely accepted among the farming community as well as consumers and thus found a place in the package of practices of the state.

4. Barriers to the Adoption of STRVs

The adoption of stress-tolerant rice varieties and associated technologies seems to offer an opportunity to increase output and income substantially. Unlike hybrid seed technology and agricultural machinery that are high-cost and capital-intensive, STRVs are low-cost technologies, having inputs and other requirements similar to prevalent HYVs. However, the adoption of stress-tolerant varieties has not reached their potential, predominantly due to distant and unreliable seed supply sources, the inadequate popularization of STRVs in farmers' networks as well as in the extension system, and the limited capacity and poor network of farmers in timely seed marketing and multiplication (Gauchan et al. 2014).

Likewise, several farmers lack awareness regarding the potential for reusing STRV seeds because they confuse them with hybrids. This poses a significant obstacle to adoption, particularly in locations where hybrids are widely cultivated and frequently advocated by private seed firms (Dar et al. 2018). Hence, the behavioral aspects of farmers' decision-making process could significantly influence the acceptance and adoption of STRVs (Yamano et al. 2013). Raising awareness of the value of STRVs is the first and most important step towards their quick and widespread adoption (Bhowmick et al. 2014). By developing a significant and consistent demand for quality seeds, proper awareness improves seed multiplication and marketing (Abebe and Alemu 2017).

5. Strategies for Enhancing Rice Production in Stress-Prone Areas

Creating awareness is a crucial initial stage for the swift expansion of new varieties, which increases demand for seeds and facilitates extensive seed multiplication. Two fundamental factors that significantly impact farmers' adoption are that the targeted technology should be relatable and relevant to local conditions (Hossain et al. 2019). The initial stage in designing a strategy to improve the adaptability of STRVs is to identify more stress-prone locations, up to the village level, using remote sensing, geographic information systems (GISs), ground information, and local revenue maps (Dar et al. 2014). Targeted seed dissemination through various demonstrations is an effective approach for STRVs, especially in the early years after their release, when seed availability is limited. The primary focus should be to organize various demonstrations in stress-prone locations, and then in less stress-prone areas, and eventually in both stress- and non-stress-prone areas, to replace the traditional HYVs with STRVs.

Scaling the adoption of STRVs among smallholder farmers must include both formal and informal seed systems. However, informal seed systems serve

as significant suppliers of seeds for several small-scale farmers worldwide. Approximately 80–90 percent of the seeds that farmers sow in their fields are obtained via informal seed channels (Saksena and Dar 2017). As a result, the informal diffusion of STRVs is critical in increasing the seed replacement rate. Thus, the IRRI is developing informal seed systems along with formal seed systems by collaborating with various stakeholders involved in the seed value chain through various interventions in Assam.

5.1. Mini-Kit Demonstrations

Seed diffusion from farmer to farmer has been proven to be an effective approach for successful distribution (Sah et al. 2021). The objective of conducting mini-kit (2–5 kg seed packets) demonstrations was to generate momentum by introducing, exposing, and providing firsthand experience with new varieties to farmers, hence encouraging the informal dissemination of seeds among the farmers. Rather than emphasizing large-scale cultivation in a few sites, the aim should be to inoculate a larger number of locations with a limited number of STRV seeds, mostly through lead farmers (Veteläinen et al. 2009). New sites are chosen in subsequent years, while farmer-to-farmer diffusion is encouraged at locations covered in earlier seasons (Dar et al. 2020). Each season, new farmers are provided with seeds and are encouraged to share them with other farmers in the following years. This approach has proven to be highly efficient in raising awareness, scaling up seeds, and promoting the adoption of STRVs in difficult yet highly targeted areas of eastern India (Coomes et al. 2015).

5.2. Head-to-Head Trials

The head-to-head (H2H) trial is one of the effective informal seed dissemination approaches. The H2H trial is a field assessment of a recently developed variety and the variety being used by the farmer. These are directly compared in terms of their yield and stress tolerance under the farmer's management (Nayak and Dwivedi, 2023). H2H trials are a useful tool for enhancing the acceptance and substitution of different varieties through the informal diffusion of seeds. In H2H trials two different varieties (STRV and farmer's variety) are evaluated under the same farmer management conditions, preferably in the same field (each half under at least 500 m^2) or two adjoining fields. The idea is to create an opportunity for the participating farmer and their fellow friends to observe and assess the advantage of STRVs over their regular ones. This has the unique feature of demonstrating the varietal advantage at the farmers' site. This makes it easy for farmers to evaluate and compare varietal gain very closely. This unique feature demonstration has been

found to be more powerful in displaying the variety for persuasive communication to farmers.

. The approach also teaches them how to evaluate data to make knowledgeable decisions regarding the acceptance of new varieties and the informal dissemination of these varieties to replace existing ones. To increase the scope, H2H trials are conducted directly on the farmer's field, allowing surrounding farmers to observe, assess, and make decisions regarding varietal selection based on their specific field needs and preferences. These demonstrations have made stress-tolerant rice varieties (STRVs) popular among eastern Indian and South Asian farmers (Sandhu et al. 2021).

5.3. On-Farm Adaptive Demonstration (OFAD)

OFADs are conducted to infer and accept the consistency of newly introduced STRVs under local conditions and management at farmers' fields under close supervision. The new varieties are evaluated under local conditions and management in the farmer's field or KVK/ZRS farm, and closely monitored by the scientists. This could help infer and acknowledge the consistency of varieties under local circumstances, actual farming systems, and local preferences which establish and generate reliable evidence about the newly introduced varieties.

5.4. Cluster Demonstration

Cluster demonstration aims to create mass awareness and generate demand for an environment-specific, modern, improved variety, sensitize visiting stakeholders, and create wide visibility. The cluster demonstrations provide substantial evidence of the performance of different varieties across various geographical locations, to generate mass visibility of new STRVs for adoption through informal seed dissemination across neighboring villages, and foster linkage and awareness among key seed-value-chain stakeholders for the new STRVs. High-yielding STRVs could be a boon for small and marginal farmers. Under APART, IRRI in collaboration with AAU, developed and/or facilitated the demonstrations of several high-yielding submergence-tolerant, short-duration, drought-tolerant, and multi-stress-tolerant varieties with both submergence- and drought-tolerance in Assam. For new varieties, these demonstration plots informally supply seeds until the varieties are infused into the formal seed chain.

5.5. Dealer Network Demonstrations

The purpose of these demonstrations is to include private entities such as seed dealers/sellers and farmer producer companies (FPCs) in promoting STRVs by

generating demand and ensuring a reliable supply, thereby improving adoption through capacity building. Since the local seed dealers have a significant influence on farmers' varietal selection, the dealer network demonstrations help trigger varietal promotion and therefore better adoption by engaging agents/institutions who receive direct benefit/incentive by promoting the variety to farmers (level of sale-volume reflects demand). These demonstrations also build the capacity and knowledge of seed dealers/agents/institutes, etc., about the varieties and their positioning.

5.6. Variety Cafeteria or Evidence Hub

The rice varietal crop cafeteria displays 15–20 promising varieties in one large plot. The newly released varieties are tested in a replicated mode against the check varieties before they are taken for further popularization through mini-kit and cluster demonstrations. Farmers, seed producers, public and private seed suppliers, distributors, and researchers are invited to observe and assess the comparative performance of those varieties. Variety cafeteria facilitates the scientific assessment and selection procedures for new varieties by farmers and other stakeholders. Variety cafeteria is a researcher-designed trial managed by the farmers themselves through proper training and orientation (Saksena et al. 2019). Farmers can use standard crop establishment and management procedures in their area, but they are also advised to avoid protecting the varieties from harsh weather conditions, pests, and diseases to emphasize the resilience of these varieties compared to locally cultivated ones. In addition to being stress-tolerant and pest- and disease-resistant, farmers can also select varieties based on their agro-morphological traits, yield, and quality attributes. The primary objective of organizing a variety cafeteria is to demonstrate a wide range of varietal options for numerous stakeholders to carry out participatory observation, selection for the region, and convince important institutions and actors to adopt new and promising varieties (Das and Nayak 2021). It entails the demonstration of various rice varieties in a certain agroecological region, giving farmers the option to select a suitable one. To promote the rapid and sustainable adoption of STRVs, the establishment of client-oriented variety cafeterias (STRV Expo) in prime locations has been advised. Farmer participatory varietal selection are conducted to evaluate varieties at crop maturity by a group of formal and informal seed stakeholders as per their preference and suitability to the agroecological environment. In participatory varietal selection, crop duration, plant height, tillering ability, disease infestation, pest infestation, grain color, grain type, and expected yield are considered for observation through scoring each plot by formal seed system stakeholders to promote the STRVs. Each plot is scored based on these observations. Variety cafeterias or evidence hubs

lead to the scientific and participatory evaluation of multiple traits of many potential varieties, eventually leading to the selection of the most appropriate variety for the locality. These hubs act as platforms for creating demand and mainstreaming selected varieties in formal seed channels for sustained production and supply through supportive policy or linkage.

5.7. Localized Seed Production

Furthermore, capacity-building programs on rigorous and practical training for trainers on quality seed production to the representatives from NGOs, extension workers, and progressive farmers improves the knowledge base and enables them to follow the recommended practices for maintaining the seed quality. Moreover, providing subsidies for the seed cost of STRVs; implementing seed village programs; creating awareness through organizing field days and farmers' fairs; distributing information pamphlets, charts, and billboards; ensuring media coverage through newspapers, TV, and radio programs; and producing documentaries, wall writings, roadside dramas, and folk songs will enhance the adoption of STRVs.

5.8. Linkages for Early-Generation Seeds (EGSs)

One of the challenges in diffusing and scaling a new potential variety is fragile linkages between breeding centers and seed multipliers. With the limited and untimely supply of EGSs (breeder/foundation), seeds are not multiplied adequately for the end-users and adoption continues to be low. The APART project made a systematic effort to bridge the gap by linking the seed accelerators—state seed corporations, private seed agencies, farmers collectives (FPO/FPC), and individual growers. With an assured supply of 11 tonnes of breeder and foundation seeds, these seed agencies could multiply around 20,000 tonnes of certified seeds, considering losses due to unpredictable weather conditions and post-harvest factors between 2019 and 2024. Looking ahead, with continued support and improved seed production practices, the seed agencies can project a significant increase in seed production annually. This will ensure a steady and reliable supply of certified seeds to farmers, meeting the growing demand for quality seeds and enhancing agricultural productivity. It catalyzes the adoption and expansion of STRVs in Assam considerably.

6. Adoption of STRVs Under APART/IRRI

One of the Project Development Objectives (PDOs) of APART "to add value and improve the resilience of selected agriculture value chains, focused on smallholder

farmers in targeted districts of the State of Assam", with the project's specific goal to strengthen the seed system and the adoption of high-yielding stress-tolerant rice varieties. Under APART, the IRRI disseminated several climate resilient technologies, with improved STRV adoption being one of the potential technologies to alleviate the hazards of climate change. STRVs covered around 0.023 Mha of area, with approximately 75,757 farmers adopting them under APART. Currently, there is a total of 0.45 Mha of area of Assam under STRVs, with around 549,879 farmers adopting them. APART focuses not only on demonstrations but also on strengthening FPCs on STRV seed production.

In Assam, the introduction of STRVs under APART since the *Sali* season 2018 has made significant headway that includes STRVs introduced during Phase I (Ranjit-Sub1, Bahadur-Sub1, Swarna-Sub1, BINA Dhan11, BINA Dhan17, DRR44) and during Phase II (BRRI Dhan69, CR Dhan 801 and CR Dhan 802). As evidenced from the crop-cut data under APART, the stress-tolerant rice varieties (STRVs) with best management practices (BMPs) could increase the grain yield by 1.2 t/ha and income by INRs 20,442/ha over farmers' preferred varieties and management practices. This has prompted the rapid spread of STRVs from 0.05 Mha in 2017 to 0.45 Mha (19 percent of total rice) in a quinquennium spanning *Sali* 2018 to 2023, to help farmers mitigate the risks of flood (1.05 Mha) as well as drought (0.2 Mha).

7. Impact of STRVs Under APART on Rice Productivity and Income of Assam

The adoption of improved seed varieties represents the most cost-effective strategy for smallholder farmers to enhance yields and profitability. The introduction of stress-tolerant rice varieties (STRVs) in Assam under the APART initiative since the *Sali* season of 2018 has achieved notable progress. From 2018 to 2024, long-duration varieties (Ranjit-Sub1, Bahadur-Sub1, Swarna-Sub1, CR Dhan 801, and CR Dhan 802), which were submergence-tolerant and multi-stress-tolerant, were cultivated on 0.21 million hectares, resulting in a production gain of 0.25 million tons and yielding farmers a net monetary advantage of 49.1 million USD. The short-duration varieties (BINA Dhan11, BINA Dhan17, and DRR Dhan 44), which are drought-tolerant, were cultivated on 0.28 million hectares, resulting in a production gain of 0.34 million tons and a net monetary benefit to farmers of 66.3 million USD. The economic advantage to the state, including in grain and straw production, totaled around 133.2 million USD due to STRVs (source: end term report APART extension phase).

8. Adaptability of STRVs in Other Regions

The Stress-Tolerant Rice for Africa and South Asia (STRASA) project was initiated by the IRRI in late 2007 in partnership with AfricaRice, aiming to develop and provide rice varieties that can withstand abiotic stresses for numerous farmers in rain-fed rice-growing regions of Asia and Africa. STRASA, designed as a decade-long initiative, provided enhanced varieties to a minimum of 18 million farmers across two continents. The project concludes with notable spillover effects for non-participating countries, especially regarding the adoption of developed stress-tolerant rice varieties and involvement in a regional seed exchange cooperation agreement. STRASA Phase 3 (2014–2019) achieved significant advancements in the release and dissemination of 71 stress-tolerant rice varieties (STRVs) across India (58), Bangladesh (6), and Nepal (7). Throughout the three phases of the project, over 150 climate-smart rice varieties exhibiting tolerance to flood, drought, and salinity, including multiple tolerances within individual varieties, were released across various countries in South Asia and Sub-Saharan Africa. The STRASA project not only enhanced varieties and distributed seeds but also trained 74,000 farmers and scientists, including 19,400 women farmers, in the production of high-quality seeds through its capacity-building initiative. This has enabled the expedited release of climate-smart varieties and enhanced seed sharing in Asia and Sub-Saharan Africa, particularly benefiting impoverished farmers who are most impacted by climate change (STRASA Legacy Site 2020).

9. Seeds Without Borders

The cross-border exchange of proven genotypes can play a significant role in improving the rice-based cropping systems. For instance, the ecosystem similarity of eastern India and Bangladesh allows the exchange of potential varieties for adoption and cultivation. Such an arrangement also reduces the duplicated expenses to develop varieties when they have already been developed in another country with a similar ecosystem. Seeds Without Borders (SWB) is a regional seed policy agreement that speeds up the distribution of modern rice varieties across countries in Asia, particularly in South and Southeast Asia. In 2014, the International Rice Research Institute (IRRI) facilitated the agreement signed by India, Bangladesh, and Nepal. To date, the agreement also includes Bhutan, Cambodia, and Sri Lanka. In 2022, the Philippines, Vietnam, and Fiji joined the agreement. Fiji is the first Pacific Island nation to join Seeds Without Borders, marking the expansion of the agreement from South and Southeast Asia to the Pacific Islands. The IRRI has been serving as a broker for this regional seed sharing agreement for almost a decade and we have seen how efficient and effective seed sharing policies across countries play an important part in

transforming their agri-food systems. Gaining access to a diverse selection of genetic resources and improved and climate-smart crop varieties enables the nations to better address the challenges in their agri-food systems. Leveraging this agreement, the IRRI in the recent past has introduced 14 varieties from Bangladesh and Nepal. Two such varieties are BINA Dhan 11 (submergence-tolerant) and BINA Dhan 17 (drought-tolerant, GSR), released by IIRR Hyderabad in 2015 and 2018, respectively. These two varieties have been crucial in Assam for protecting farmers from yield penalties during submergence and drought.

10. GIS Technology for Varietal Targeting

The adoption of a certain technology could be increased if it is placed in areas where it could achieve the highest benefit. The geospatial products developed by the experts in APART have helped in the precise identification of stress-prone areas and soil moisture suitability in these regions. This further helped in targeted dissemination of suitable crops, and the technologies and innovations promoted under the project.

11. Conclusions

Innovative extension methods are pivotal in creating awareness and spreading varietal awareness in the targeted regions. The aforementioned integrated extension model aiming to boost the demand side was a proof of concept for further replication and adoption by extension machinery. The localized seed access catalyzes the spread of new promising varieties. Through the IRRI-APART project in Assam, formal, informal, and semi-formal seed systems in the state are visualized to be strengthened to ensure the access, production, and supply of quality seeds of these new or introduced STRVs. By stakeholder engagements for breeder seed and foundation seed production and multiplication through research institutes and centers in the state, the local availability of these STRVs aims to be ensured. By engaging delivery agents like local seed dealers and farmers in the entire extension process, both formal and informal channels of seed supply and demand will be strengthened through this project.

Long-term adverse impacts of climate change, including various abiotic stresses, are anticipated to pose a significant obstacle to the sustained production of rice in the near-future. Assam possesses the potential to achieve significant agricultural productivity and production by leveraging its inherent resources and advantages. However, climate change has threatened the sustained growth of rice and other crops. Developing rice varieties that possess stress tolerance with higher grain

yield and desirable quality is the most reasonable strategy to address the challenges posed by climate change. STRVs provide prospects for enhancing and stabilizing rice yields in stress-prone areas, thereby making a substantial contribution to the overall food security of the nation. These varieties also offer additional possibilities for increasing annual productivity through the utilization of inputs and modifying cropping patterns. They will not only improve but also stabilize rice productivity in stress-prone areas. In addition to the quick advancements in the development of stress-tolerant rice varieties, it is necessary to consistently make efforts to disseminate and facilitate the adoption of these varieties in targeted locations. Hence, implementing a focused scaling in vulnerable regions will significantly affect the food security of small-scale farmers residing in those fragile ecosystems.

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Best Agronomic Practices to Mitigate the Transition of Climate Action

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1. Introduction

The Sustainable Development Goals (SDGs) provide interconnected global objectives across economic, social, and environmental dimensions to guide sustainable development by 2030 (Figure 1) (United Nations 2023). The 13th SDG focuses specifically on climate change mitigation and adaptation, which address immediate solutions to fight against climate impacts that disproportionately affect the most vulnerable populations (Sachs et al. 2019). Strategies include strengthening national resilience, enhancing climate change education, improving early warning systems for climate disasters, and tracking finance flows that either mitigate or worsen climate change (United Nations 2023).

Agriculture is important in pursuing climate mitigation and adaptation due to its complex relationship with climate change. Agriculture simultaneously contributes to and is threatened by climate change, necessitating a shift to more sustainable practices that reduce greenhouse gas (GHG) emissions and increase resilience. Sustainable practices aim to reduce GHG emissions, enhance soil health and water conservation, and enhance the ability of crops and livestock to withstand the effects of climate change (Malhi et al. 2021). The nature-based solutions (NBSs) are identified as a sustainable way of restoring ecosystems while simultaneously benefiting human well-being. The NBS improves productivity while yielding climate benefits. NBSs contribute to ecosystem restoration and improve biodiversity. Implementation of best agronomic practices in farming is a major concern in NBS. Based on their primary contribution to either climate change mitigation or adaptation, these advanced agronomic practices can be categorized as 'mitigation strategies' and 'adaptation strategies'. Mitigation strategies aim to reduce greenhouse gas emissions or enhance carbon sequestration and include practices such as minimal soil disturbance, continuous soil cover, improved nutrient cycling, agroforestry, organic farming,

carbon farming, and precision agriculture technologies (e.g., variable rate application, remote sensing, AI-based decision tools). On the other hand, adaptation strategies are designed to enhance the resilience of farming systems to climate-related stressors and include crop diversification, crop rotation, intercropping, cover cropping, integrated pest management, drought-tolerant crop varieties, and soil health management practices, such as mulching and water conservation. While some practices (e.g., agroforestry, organic farming, and precision agriculture) offer co-benefits for both mitigation and adaptation, clearly distinguishing their primary function improves the applicability of this review for decision-makers and practitioners.



Figure 1. Sustainable Development Goals: The three dimensions of sustainable development. Source: Figure by authors.

Integration of Agronomic Practices with SDG 13: Climate Action

The adoption of best agronomic practices plays a pivotal role in achieving SDG 13, which calls for urgent action to combat climate change and its impacts. Practices such as conservation agriculture, agroforestry, biochar application, and precision farming directly contribute to reducing GHG emissions and enhancing carbon sequestration, thereby supporting climate mitigation efforts. Furthermore, interventions like integrated nutrient management, cover cropping, and organic farming promote the restoration of soil health and resilience, aligning with SDG 13.1,

which emphasizes strengthening resilience and adaptive capacity to climate-related hazards. Efficient water management, the use of climate-resilient crop varieties, and integrated pest management (IPM) contribute to more sustainable land and resource use, addressing the need for climate-responsive planning highlighted in SDG 13.2. These practices also embody the spirit of SDG 13.3 by fostering awareness and capacity building among farming communities through knowledge-intensive, low-carbon agricultural approaches. Thus, integrating these agronomic strategies not only advances climate-smart agriculture but also positions the farming sector as a critical contributor to global climate action.

While individual practices have been studied extensively, there is a lack of comprehensive synthesis that integrates these agronomic practices specifically under the framework of nature-based solutions and evaluates their multifunctional roles in climate mitigation, resilience building, and ecosystem restoration. This chapter will provide a comprehensive review of best agronomic practices to support the transition from conventional agriculture to climate-smart agriculture using the latest scientific evidence and real-world knowledge. It aims to inform policy and decision-makers towards sustainable farming systems that address climate change while ensuring food security and rural livelihoods.

2. Methodology

This review employed a systematic narrative approach to synthesize existing evidence on agronomic practices that contribute to climate change mitigation and adaptation. A comprehensive literature search was conducted using five major academic databases: Web of Science, Scopus, Google Scholar, PubMed, and Science Direct. The search focused on studies published between 2000 and 2025, with additional inclusion of earlier seminal works where relevant. Search terms included combinations of keywords, such as "*conservation agriculture*," "*agroforestry*," "*organic farming*," "*climate change*," "*carbon sequestration*," "*greenhouse gas*," "*mitigation*," and "*adaptation*." Only literature published in English was considered.

To ensure relevance and quality, the review included peer-reviewed journal articles, field studies, meta-analyses, systematic reviews, and technical reports from international organizations. The selection criteria emphasized studies that provided quantifiable climate impacts, particularly those assessing GHG reduction and carbon sequestration evaluated adaptation co-benefits of agronomic practices. While the scope was global, special attention was given to evidence from developing countries, where agricultural vulnerability to climate change is typically higher.

3. Conservation Agriculture

Conservation agriculture is a holistic farming system that can prevent losses of arable land while regenerating degraded lands through a comprehensive approach to sustainable production that aims to maintain high agricultural yields while minimizing negative environmental impacts. Central principles encompass building long-term soil health, increasing biodiversity, improving resource efficiency through ecological processes, and enhancing overall resilience to intensifying climate shifts and weather extremes (Kassam et al. 2019). Practices are adapted to local conditions, focusing on the synergistic application of soil, water, nutrients, carbon, and pest management strategies that are context-specific (Joshi 2011). Core techniques aligned with conservation goals include minimizing mechanical soil disturbance while maintaining permanent organic soil covers, implementing regular crop rotation, and integrating multi-species interactions, either sequentially over seasons or concurrently through polycultures (Hobbs 2007). Appropriate Integrated Pest Management (IPM), which uses biological and genetic controls instead of broad-spectrum pesticides, improves system regulation (Ciancio and Mukerji 2007). Site-specific nutrient budgeting and mixed organic/inorganic fertilization maintain function while reducing off-site pollution and emissions-intensive inputs (Tilman et al. 2017). The combination of these complementary techniques preserves critical resources for long-term production and environmental quality. Conservation agriculture is based on five fundamental concepts (Figure 2).



Figure 2. Principles of conservation agriculture. Source: Figure by authors.

3.1. Minimal Soil Disturbance

Minimum soil disturbance is a basic concept in conservation agriculture, and it comprises reducing mechanical soil disturbance using no-till or minimum-tillage methods (Figure 3). According to Hobbs (2007), reducing mechanical soil disturbance helps to preserve the soil structure and ecosystem. Tillage operations can be eliminated or reduced to retain the physical, chemical, and biological qualities of the soil, resulting in improved soil health and stability over time.



Figure 3. (**a**) Conventional tillage vs. (**b**) minimum tillage. Source: Figure by authors. (Photographs were captured at the Coconut Research Institute, Bandirippuwa Research Center, Lunuwila (7.332201° N, 79.881737° E)).

Reduced tillage promotes climate resilience by reducing erosion, which has been accelerated by climate change. Rusu et al. (2009) discovered that using minimal tillage practices can reduce soil erosion rates by up to 90%, protecting topsoil needed to maintain agricultural productivity against climate-related challenges. Minimum tillage also increases permeability, which promotes biological activity and nutrient availability. Compared to intense conventional tillage, minimum tillage improves erosion resistance and crop yields by more than 80%. Cultivating across slopes with minimum tillage has been shown to reduce runoff and erosion on sandy soils. This emphasizes that less tillage improves soil conservation, which is important for agricultural production with rapid climate change.

The findings of Franzluebbers (2004) indicate that no-till and strip-till enhance climate resilience by enhancing moisture conservation and biological mechanisms in the soil. Strategies that minimize mechanical disturbance and retain protective surface mulch have been shown to improve soil structure and organic matter content. Enhanced soil aggregation increases infiltration and storage compared to intensive tillage. Over time, organic matter accumulation protects crops from drought by

increasing the water-holding capacity (Lotter et al. 2003). Reducing compaction enables better development of roots and passages for water flow and use efficiency (Chen and Weil 2010). While the efficacy of outcomes is influenced by specific crop rotations and soil types, empirical research suggests that systems employing minimal disturbance significantly improve soil moisture availability and access, as well as resilience to water deficits (Rusu 2014).

Beyond moisture retention, minimal tillage creates a habitat for beneficial micro-biota while allowing crops to root more extensively through less compacted structures, and it reduces the fuel requirement for agricultural activities (Williams and Weil 2004). The combined biological and physical shifts confer resistance advantages against various stresses like extreme heat, pests, and crop diseases (Pereg and McMillan 2015). Even though balanced nutrient inputs are important, studies show that regenerative minimal tillage techniques can make crops much more productive and protect them against climate change threats (Verhulst et al. 2011).

3.2. Continuous Soil Cover

Continuous plant cover or crop residue on agricultural land provides major climate mitigation advantages by reducing CO_2 emissions, improving soil moisture retention, and increasing soil carbon storage (Lal 2004). Bare soil is prone to erosion and carbon loss, while cover acts as a protective barrier, maintaining reserves. Both living covers like cover crops and grasses and non-living mulches safeguard soil, enhance nutrients, and support sustainability. Although synthetic covers have benefits, plant-based covers are more effective for soil health and carbon sequestration through photosynthesis and biomass incorporation (Kaye and Quemada 2017). Employing diverse regional soil covers allows farmers to optimize climate impact reduction while boosting productivity and resilience.

3.2.1. Living Mulches

Using living mulches, or growing cover crops concurrently with cash crops, provides ecological and soil benefits that can increase the resilience of agricultural systems to climate change effects, while cash crops enhance the profitability of the farming system (Figure 4) (El-Beltagi et al. 2022). Integrating legume-derived living mulches especially fixes atmospheric nitrogen. In crop–livestock systems, cover crops reduce emissions compared to standard techniques. In a nutshell, the broad application of living mulches is necessary to create robust, eco-friendly agricultural systems by stabilizing yields, improving soil resilience, reducing emissions, and sequestering carbon (Dissanayaka et al. 2022; Dzvene et al. 2023).

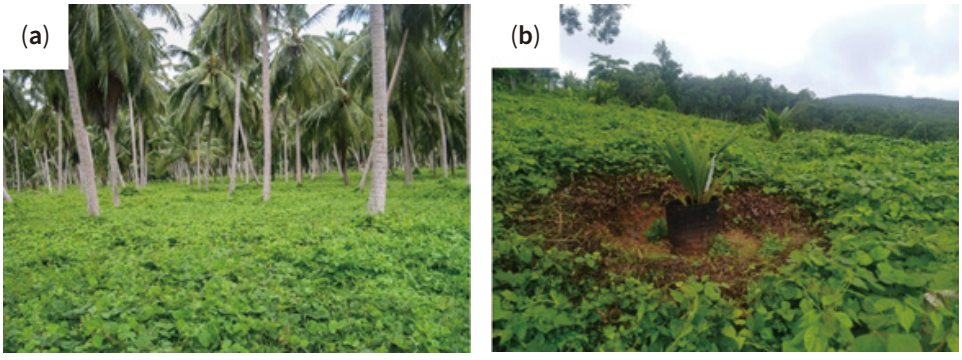


Figure 4. Living mulches with (**a**) *Pueraria phaseoloides* and (**b**) *Mucuna bracteata* in coconut plantations. Source: Figure by authors. (Photographs were captured at the Coconut Research Institute, Walpita Research Center, Walpita (7.272118° N, 80.034855° E)).

3.2.2. Non-Living/Dead Mulches

Non-living (dead) mulches, such as decomposing crop residues or organic materials applied to the soil, can also be used as soil covers (Figure 5). Coconut fronds, coconut husks, removed weed trash, pruned vegetative parts of intercrops, and livestock manure can be used as dead mulch around the coconut palms. Organic matter is absorbed into the soil through the breakdown process of decaying mulches, which contributes significantly to carbon sequestration (Fracchiolla et al. 2020). Smith et al. (2015) stated that having dead organic matter on the soil surface is critical for soil carbon sequestration, which involves capturing and storing carbon in soil, which reduces carbon dioxide levels in the atmosphere.

Both living and dead mulches improve soil health and fertility by enhancing physical properties such as structure, moisture retention, and nutrient availability, hence increasing productivity and reducing dependence on inorganic fertilizer (Ngosong et al. 2019). They protect soil from erosion and adverse weather conditions, regulate temperatures, and retain moisture (Li et al. 2022). Both mulches also support beneficial organisms that prevent pests and are involved in nutrient cycling, reducing pesticide and fertilizer utilization, suppressing weeds, and reducing nitrous oxide emissions by increasing soil health (Smith et al. 2015). They offer climate adaptation benefits in both natural and urban contexts, such as preserving biodiversity and reducing cooling energy consumption.



Figure 5. Dead mulches applied to coconut plantation. Source: Figure by authors. (Photographs were captured at the Coconut Research Institute, Ambakelle Research Center, Ambakelle (7.696934° N, 79.893901° E)).

3.3. Crop Diversification

Crop diversification is an effective strategy to adapt to climate change, defined as a procedure that introduces new crops to diversify a simple farming system throughout time and location (Hufnagel et al. 2020). Integrating various crops, types, and cropping practices strengthens resilience to rising temperatures, shifting rainfall, and weather extremes that affect agricultural output and revenue (Giannarakis et al. 2023). Strategically rotating cereals with legumes, intercropping compatible species, and incorporating stress-tolerant genotypes can stabilize yields across variable conditions (Kumar and Khurana 2023). Beyond climate adjustment, diversification provides additional ecosystem services vital for sustainability. Adapted to local contexts, multi-crop systems employ genetic, species, and system diversity to facilitate climate adaptation and promote sustainability in next-generation agriculture (Atapattu et al. 2024).

3.3.1. Crop Rotation

Crop rotation is a systematic agricultural technique that involves planting many crops on the same land. This strategy is important to mitigate the negative consequences

of climate change on the agricultural sector. Crop rotation can withstand and adapt to changing meteorological conditions caused by the phenomenon of climate change (Yu et al. 2022).

Crop rotation is beneficial for climate change resilience, as it improves soil health and fertility. According to Drinkwater and Snapp (2007), including a range of root systems is beneficial for stabilizing soil structure, replacing nutrients at different depths, and reducing pest infestations. As a result, the soil becomes more resilient and can resist extreme weather events. Crop rotation, which alternates across crop families such as legumes, cereals, and brassicas, interrupts the cycles of certain pests and diseases, improving yield stability under changing climatic conditions. Furthermore, it enhances moisture retention (Basche et al. 2016). And this practice reduces reliance on synthetic fertilizers and pesticides, thereby lowering GHG emissions in agriculture (Glover et al. 2010).

Studies have shown that diversified crop rotations significantly reduce GHG emissions from agriculture when compared to continuous cropping (Gelfand et al. 2013). Aside from climate mitigation, it enhances biodiversity by selectively sequencing crops to increase botanical variety throughout time (Schulte et al. 2014). This creates habitats for a variety of insects, birds, and soil creatures, increasing ecosystem resilience to increasing climate extremes. Furthermore, adding perennial cereals into crop rotations has the potential to improve soil carbon absorption while lowering crop emissions (Culman et al. 2013). Furthermore, integrated crop-cover crop–livestock rotations with rotational grazing increase soil carbon absorption, demonstrating the potential of crop rotations to capture GHGs (Machmuller et al. 2015). Crop rotations work better when combined with complementary strategies like cover cropping, IPM, and no-till farming (Pittelkow et al. 2015).

3.3.2. Intercropping

Intercropping, or the cultivation of various crops in a shared space, increases agricultural resistance to climate change (Figure 6). Strategically combining complementary plants with different growth patterns, resource demands, and root structures enhances both above- and below-ground biodiversity (Atapattu et al. 2017). This synergistic variety increases the farmers' income more than monocultures (Liu et al. 2023). It also improves soil health by increasing carbon storage, which reduces CO_2 emissions. When carefully arranged to local conditions, this system has been shown to maintain production with shifting precipitation patterns, rising temperatures, and extreme weather events, which cause significant

risks to monoculture systems (Brooker et al. 2015). Intercropping with a variety of crops maximizes moisture, nutrients, and light capture under suboptimal conditions (Lithourgidis et al. 2011). When intercropping is performed sustainably, it enhances the interplay between genetic and species variety both above and below the soil surface. Glaze-Corcoran et al. (2020) give scientific research findings demonstrating that this technique has significant potential to sustain food production effectively under rising global climate extremes.

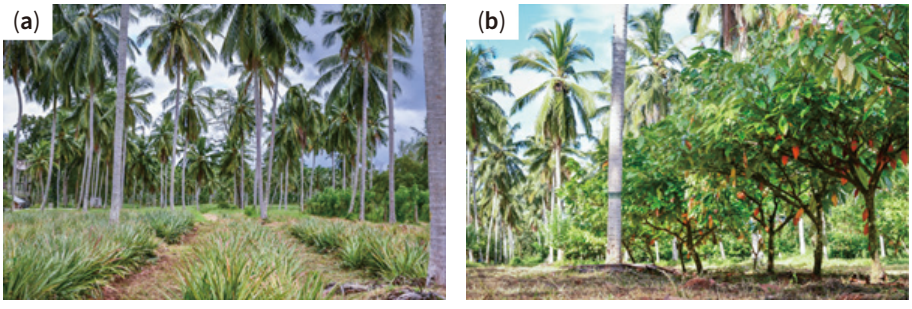


Figure 6. Coconut plantations intercropped with (**a**) pineapple and (**b**) cocoa. Source: Figure by authors. (Photographs were captured at the Coconut Research Institute, Makandura Research Center, Makandura (7.319424° N, 79.983393° E)).

Studies on intercropping emphasize its efficacy in mitigating the impacts of climate change and consistently demonstrate the potential to increase yields in contrast to monocropping (Liu et al. 2023). Additionally, intercropping serves as a resilience-building measure against drought, as exemplified by maize–soybean intercrops maintaining yields under drought stress, while sole crops experienced yield declines of 15–20% (Mao et al. 2012). Combining crops with various root depths, such as cereals and legumes, optimizes water and nutrient utilization within intercropped systems (Brooker et al. 2015). Furthermore, it is important to acknowledge that intercropping has been observed to contribute to the augmentation of carbon sequestration in soils. Studies indicate that intercropping systems have the potential to enhance climate resilience and mitigate the impact when sustainably implemented (Cong et al. 2014). Intercrops also suppress weeds through enhanced competition, reducing pesticide needs (Szumigalski and Van Acker 2006). Nevertheless, inadequate species selection and ineffective management practices can intensify competition and diminish crop productivity (Brooker et al. 2015). When designed with context-specific factors, intercrops use biodiversity and synergies above and below ground to buffer climate change. The evidence supports the

conclusion that intercropping can sustainably enhance agricultural adaptation in response to climate change.

3.3.3. Cover Cropping

Cover cropping is a technique that entails the cultivation of specialized crops to safeguard and maintain the soil during periods between primary crop cycles and has been demonstrated to augment climate resilience through a range of mechanisms (Kaye and Quemada 2017). Cover crops like legumes, fodder, and pasture grasses are in high demand worldwide due to variations in climatic conditions across different regions (Table 1). Cover cropping provides several benefits, including a significant reduction in soil erosion (Nuwarapaksha et al. 2023b). Kaspar and Singer (2015) discovered that cover cropping considerably reduces soil erosion compared to bare soil, with reductions ranging from 60% to 100%. This reduction in erosion helps to improve water retention and nitrogen levels in the soil. Furthermore, incorporating organic matter through the use of cover crop residues enhances soil carbon concentrations, improving soil moisture absorption and supporting the long-term retention of carbon (Poeplau and Don 2015).

Finney et al. (2017) demonstrate that utilizing diverse cover crop species promotes the growth and performance of beneficial soil microorganisms and improves nitrogen cycling. This method significantly benefits plant development, particularly under variable environmental conditions.

Cover crops conserve water by successfully mitigating runoff and evaporation, facilitating soil infiltration, and improving drought tolerance (Kaye and Quemada 2017). Moreover, they play a role in the suppression of weeds by restricting access to light and nutrients necessary for plant proliferation, thereby diminishing the need for pesticides. In addition, it has been observed that legume cover crops have the ability to engage in nitrogen fixation, whilst non-legume types contribute to the absorption of surplus soil nitrogen. Consequently, the aforementioned dual action functions to reduce leaching and limit the emission of GHGs into the environment (Thapa et al. 2018). The utilization of cover cropping presents a multifaceted and inclusive approach to bolster the adaptability of agriculture in the face of climate change, therefore making it an advantageous and sustainable strategy within the context of climate-smart agriculture.

Table 1. Prominent cover crops in tropical and temperate regions.

Region	Common Name	Scientific Name
Tropical	Alfalfa	*Medicago sativa*
	Brazilian style	*Stylosanthes guianiensis*
	Buffalo bean	*Mucuna aterrima*
	Calopo	*Calopogonium mucunoides*
	Centro/Butterfly pea	*Centrosema pubescens*
	Cluster bean	*Cyamopsis tetragonoloba*
	Gliricidia	*Gliricidia sepium*
	Mucuna	*Mucuna* spp.
	Jumbie bean	*Leucaena leucocephala*
	Lablab	*Lablab purpureus*
	Mung bean	*Vigna radiata*
	Pigeon pea	*Cajanus cajan*
	Pueraria	*Pueraria phaseoloides*
	Soybean	*Glycine max*
	Sunn hemp	*Crotalaria juncea*
	Velvet bean	*Mucuna deeringiana*
	Wild sunflower	*Tithonia diversifolia*
Temperate	Alfafa	*Medicago sativa*
	Barrel medic	*Medicago truncatula*
	Black lentil	*Lens culrnaris*
	Common vetch	*Vicia sativa*
	Crimson clover	*Trifolium incarnatum*
	Cura clover	*Trifdium ambiguum*
	Nanoleaf vetch	*Vicia angustifolia*
	Purple vetch	*Vicia benghalensis*
	Red clover	*Trijblium pratense*
	Soybean	*Glycine max*
	Sweet clover	*Melilotus oficinalis*
	Winter pea	*Pisum sativum*

Source: Authors' compilation based on data from Dissanayaka et al. (2022); Fageria et al. (2005); Scavo et al. (2022).

3.4. Integrated Pest Management (IPM)

Climate change is expected to alter patterns of crop pest pressure and outbreak severity in complex ways (Deutsch et al. 2018). Rising temperatures, shifting precipitation, increased flooding, droughts, and extreme weather events all influence pest ecology across scales. Integrated pest management provides a proven, science-based approach to maintain productivity despite such changes. IPM utilizes a broad spectrum of biological, cultural, and chemical controls to limit reliance on pesticide inputs with increased carbon footprints (Ciancio and Mukerji 2007).

Prioritizing natural enemies is core to IPM climate strategies. Warming may increase the overwinter survival of beneficial insects providing biological control of pests (Thomson et al. 2010). However, extreme temperatures can reduce biocontrol efficacy (Chen and McCarl 2001). Providing refugia habitats with flowering plants and managed bee populations helps maintain control capacity. Monitoring informs selective interventions, optimizing biological regulators (Dara 2019).

Diversifying crop varieties serves as a buffer against environmental fluctuations, and combining pest-resistant genetics with different maturities improves resilience to novel conditions and outbreaks, thereby securing yields (Tooker and Frank 2012). Refugia strips further attenuate the spread of specialist pests between fields (Barbercheck and Wallace 2021).

While IPM must evolve with climate shifts, established principles and practices build adaptation capacity. Using ecologically based, site-specific management and scientific monitoring to minimize pesticide inputs makes production more resilient and sustainable amid intensifying pressures (Ciancio and Mukerji 2007).

3.5. Improved Nutrient Cycling

Climate change is altering nutrient dynamics in complex ways, affecting crop productivity and environmental impacts. Improved nutrient cycling focuses on optimizing fertility inputs while minimizing losses to air and water. Adding organic amendments like compost, manure, and cover crop residues builds soil organic matter, enhancing nutrient retention while sequestering carbon (Kallenbach et al. 2016). Inorganic fertilizers remain key to meeting crop demands, but refinements in application timing, placement, and site-specific nutrient budgets based on soil tests and precise field monitoring can reduce excess use and pollution (Robertson and Vitousek 2009).

Introducing leguminous cover crops and interspersed plantings provides biological nitrogen fixation to reduce synthetic fertilizer requirements (Nuwarapaksha et al. 2023a; Baldi et al. 2010). Substituting organic sources for inorganic inputs

improves nutrient cycling, lowering production emissions while often maintaining or boosting yields (Skinner et al. 2019). With climate shifts altering soil processes and plant demands, farmers must adaptively manage dynamic nutrient cycles. However, following core soil health principles can make systems more resilient to change while mitigating the climate impact of agriculture.

4. Agroforestry

Agroforestry is a method of land use that intentionally integrates the cultivation of perennial woody plants with the raising of crops and/or livestock on the same piece of land. As an integrated system, agroforestry creates environmental, economic, and social benefits that exceed the value of its individual components (Jose and Gordon 2008; Dissanayaka et al. 2023a). The practice of agroforestry is gaining recognition as an ecologically viable strategy that holds promise for mitigating climate change. Agroforestry effectively sequesters and stores CO_2 through tree photosynthesis, enabling greater carbon storage per area than conventional farming. It has significant carbon sequestration potential, making it valuable for carbon offset programs seeking agricultural carbon neutrality. Agroforestry also enhances resilience by diversifying land use and sheltering crops (Jose 2009). It also increases soil fertility and structure while decreasing erosion and conserving moisture (Senarathne and Udumann 2019). Integrating trees increases soil carbon sequestration potential (Jose 2009). Alley cropping is one of the most successful strategies for enhancing plant and soil carbon stocks (Hombegowda et al. 2022).

5. Organic Farming

The use of synthetic fertilizers, conventional tillage, and changes in traditional agricultural land use have a significant impact on GHGs emissions (Vermeulen et al. 2012). Traditional farming practices can effectively retain carbon in both soil and vegetation (Paustian et al. 2016; Lal 2004). The importance of organic farming has grown in recent years, as it utilizes ecological processes while avoiding the use of synthetic chemicals. This technique has received attention for its potential to fight against climate change.

According to Gattinger et al. (2012), organic farming practices can effectively reduce GHG emissions and increase carbon sequestration in agricultural systems by cutting agricultural emissions through practices like eliminating nitrogen fertilizers, increasing soil organic carbon reserves by an average of 28% compared to conventional farming (Marriott and Wander 2006), decreasing fossil fuel dependence by limiting the use of high energy inputs, and promoting on-farm biodiversity

that facilitates carbon capture and climate resilience (Figure 7) (Lorenz and Lal 2016). Organic agriculture takes a holistic approach to mitigate the climate impact of agriculture through reduced GHG releases, enhanced soil carbon storage capacity, efficient energy use, and habitat preservation while also maintaining productive outputs and food security (Ponisio et al. 2015), underscoring its role as a sustainable climate change solution.

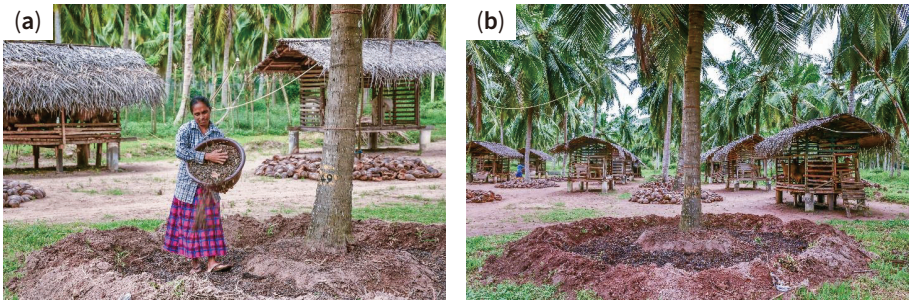


Figure 7. Application of organic manure for coconut palms (**a**,**b**). Source: Figure by authors. (Photographs were captured at the Coconut Research Institute, Rathmalagara Research Center, Rathmalagara (7.543307° N, 79.890113° E)).

6. Improved Livestock Management

The global livestock sector is a substantial contributor to climate change (Figure 8). Enteric fermentation of feed in ruminants, land use for livestock, and feed production operations generate approximately 14.5% of the total global anthropogenic emissions of GHGs (Gerber et al. 2013). Meanwhile, increased atmospheric temperatures and carbon dioxide concentrations, the occurrence of more variable precipitation patterns, and extreme events due to climate change have negatively affected the global livestock production return (Solomon et al. 2007). It is now clear that the livestock sector has been adversely influenced by reduced feed intake, milk and meat output, decreased reproductive performance, impaired immunological systems, and increased livestock mortality.

Furthermore, the livestock sector has been indirectly affected by changes in feed crop production; other herbage composition and production; quality of forage; reduced water availability and increasing water use; significant seasonal variation in resource availability; and increased disease, pest, and parasite stress (Cheng et al. 2022). Regardless, the global livestock sector continues to grow further to fulfill the demand for livestock products. Considering the adverse effects of ongoing climate change actions on livestock production, as well as continued pressure on the

environment, adaptation and mitigation actions for climate change, particularly for livestock production-related activities, are required and have been identified globally (Collier et al. 2019).

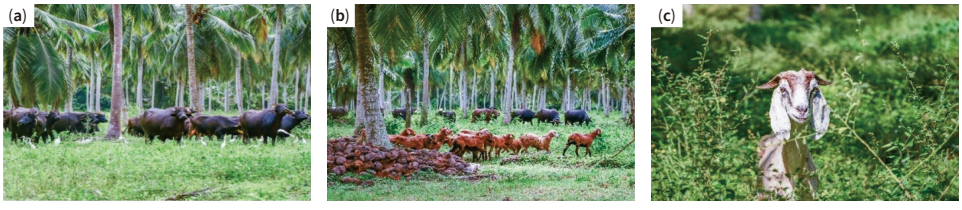


Figure 8. Livestock integration in coconut plantations; (**a**) buffalo farming; (**b**) sheep farming; and (**c**) goat farming. Source: Figure by authors. (Photographs were captured at the Coconut Research Institute, Rathmalagara Research Center, Rathmalagara (7.543307° N, 79.890113° E)).

Climate change-related stresses have caused physiological, biochemical, immunological, anatomical, and behavioral adaptations of livestock animals (Ratnakara et al. 2017). Additionally, shade seeking, increased sweating and panting, increased water intake and drinking frequency, increased standing time and decreased lying time, and decreased feces and urination frequency (Gaughan et al. 2019) are found to be the temporal adaptations of livestock animals to climate change. In addition, human interventions, such as animal breeding to produce heat-tolerant animals, provision of physical modifications to cope with heat stress (Schauberger et al. 2019), feed and pest management (Renaudeau et al. 2012), introduction of livestock systems to diversify livestock species (Martin et al. 2020), adjustments of stocking rate (Díaz-Solís et al. 2009), and integrating livestock system with forestry or crops (Alves et al. 2017), have been adopted globally as adaptation measures to climate change. As per the intention of this review, those animal-based or human-intervened adaptations to climate change are not further discussed here.

Mitigation measures can be used to reduce livestock GHGs emissions. Mitigation potentials, however, vary depending on the production systems and regions of livestock production (Gerber et al. 2013). In general, the following measures have been identified in the world as mitigation measures to reduce the contribution of the livestock sector to climate change actions.

To mitigate the release of methane, it is imperative to employ improved feeding practices, incorporate nutritional supplements, and embrace selective breeding techniques to minimize methane production (Hristov et al. 2015). Further, Gerber et al. (2013) reported that improving the feed efficiency and quality (e.g., improved digestibility, low-fiber diets, and probiotics-incorporated diets) provides advantages for both livestock production and the decrease in GHG emissions. Land resource management through improved grazing management, altering grazing intensity, and/or manure use to enhance carbon sequestration can also reduce the emission of GHGs from livestock animals. Wang et al. (2015) argued that the adoption of sustainable grazing management strategies, such as the incorporation of rotational grazing systems, can effectively address the adverse consequences of overgrazing and soil degradation. Gerber et al. (2013) also reported that the efficient utilization of resources in cattle production reduces the total environmental impact. Appropriate manure management strategies, such as anaerobic digestion and composting, capture and transform methane emissions into usable energy, hence reducing environmental effects (Dissanayaka et al. 2023b; Petersen et al. 2013). The incorporation of agroforestry into livestock systems improves the process of capturing and storing carbon, while the implementation of climate-resilient breeding enhances the overall ability to withstand and adapt to climate change (Thornton and Herrero 2014). Moreover, fertilizer management through increased nitrogen efficiency in grazing lands and nitrogen use by using manure can help reduce GHGs production. The practice of improved livestock management involves the implementation of a few or many of the above strategies that collectively reduce climate change impacts.

7. Soil Health Management

Soil health management is crucial for building climate resilience into agricultural systems while mitigating sector emissions through organic carbon sequestration. Core soil health practices encompass a diverse array of regenerative farming techniques that enhance soil structure, health, and biodiversity to improve crop yields, nutrient and water cycling, and the abilities of ecosystems to withstand intensifying climate extremes (Kassam et al. 2014). Central practices include reduced/no-till methods, cover cropping, diverse crop rotations, agroforestry, intercropping systems, organic soil amendments, and holistic nutrient and water management (Brooker et al. 2015; Lal 2004).

By reducing mechanical disturbance, strategies like low/no-tillage, cover crops, and permanent agroforestry plantings conserve soil structure and organic matter while decreasing erosion losses (Jose 2009; Powlson et al. 2014). Maintaining living roots and minimizing bare fallow periods feed soil biology, build fertility, and increase carbon inputs through residue retention and root exudates (Basche and DeLonge 2017; Blanco-Canqui et al. 2015). Similarly, applying organic amendments like manures, composts, and biochar introduces stable carbon compounds, nutrients, and microbiota to enhance biological functioning (Ding et al. 2014; Ekanayaka et al. 2023). All nourish valuable soil structures and food webs to enable climate resilience.

In turn, cover crops, intercropping, diverse rotations, and strategic integration of nitrogen-fixing species optimize soil nutrient balances and water availability while adapting environments to stabilize yields (Brooker et al. 2015; McDaniel et al. 2014). Healthy, biologically active soils reduce reliance on synthetic fertilizers and irrigation through optimized cycling processes (Robertson and Vitousek 2009). By curtailing external inputs with emissions footprints, regenerative practices offer mitigation opportunities.

Crucially, many soil health techniques directly sequester atmospheric carbon into stable soil organic matter fractions. Building soil carbon sinks not only boosts resilience but also offsets agricultural emissions for climate change mitigation (Lal 2004; Tilman et al. 2002). The compounding benefits span increased fertility, yields, and incomes alongside environmental gains. Holistic soil health management thus provides a powerful paradigm for establishing resilient, ecologically aligned, and low emissions agricultural systems amid rising climate risks.

8. Carbon Farming

Carbon farming involves implementing practices that capture atmospheric carbon dioxide through plants and store it in soils (Lal 2004). Key practices include cover cropping, no-till farming, nutrient management, agroforestry, and rotational grazing (Paustian et al. 2016). Cover crops cultivated between cash crop seasons absorb carbon through photosynthesis and release certain carbon molecules into the soil via root exudates and crop residues (Poeplau and Don 2015). No-till farming reduces soil disturbance and promotes soil carbon buildup (Powlson et al. 2014). Balanced fertilization provides nutrient inputs to crop requirements, promoting plant development and carbon return to soils (Robertson and Vitousek 2009). Agroforestry involves incorporating trees into agricultural systems, which increases overall biomass production and carbon storage (Jose 2009; Dissanayaka et al. 2023a). Rotational grazing encourages pasture regeneration, which promotes soil carbon

sequestration (Wang et al. 2015). Additional measures such as compost additions, biochar applications, proper irrigation, and silvopasture can also help with carbon sequestration (Lorenz and Lal 2014).

Adapting carbon farming throughout agricultural lands has the potential to significantly reduce GHG emissions while improving soil health and farming output. Carbon farming sequesters atmospheric carbon in soils and plant biomass. Cover cropping, no-till farming, and agroforestry improve natural carbon capture processes by increasing soil carbon stocks (Paustian et al. 2016). This directly reduces GHG levels that contribute to climate change. Carbon farming also reduces the demand for fossil-fuel-intensive inputs, such as fertilizers and pesticides, resulting in lower agricultural emissions (Kaye and Quemada 2017). The associated improvements in soil health and fertility also improve climate resilience of farming systems against weather extremes while increasing yields and reducing emissions from land clearing (Lal 2015).

Beyond climate mitigation, carbon farming provides improved air and water quality, increased biodiversity, and support for rural livelihoods (Smith et al. 2008). With several advantages and easy approaches, carbon farming has greater potential to contribute to global efforts to prevent climate change impacts through natural and sustainable land management.

9. Precision Agriculture Technologies for Climate Mitigation

Precision agriculture technologies transform crop production by enabling more sustainable and efficient agricultural practices. These technologies utilize data-driven approaches to optimize the management of crops, soil, and resources, making them powerful tools for climate mitigation in agriculture (Table 2).

Success in precision agriculture for climate mitigation depends fundamentally on taking a systematic approach that combines multiple precision technologies rather than implementing isolated solutions, creating synergies that amplify climate benefits while improving operational efficiency. Critical to this success is effective data integration that seamlessly links sensor data with real-time management decisions, enabling farmers to respond quickly to changing conditions and optimize resource use for maximum climate impact. Continuous monitoring forms the backbone of effective implementation, requiring regular assessment of climate impact through ongoing measurement and evaluation to ensure that precision agriculture practices are delivering the intended environmental benefits while maintaining agricultural productivity. Table 3 shows the use of the discussed best agronomic practices in the real world.

Table 2. Core precision agriculture technologies and climate impact.

Technology	Description	Climate Mitigation Mechanisms	Specific Applications	Benefits	References
Variable Rate Application (VRA)	Automated application of materials based on sensor data, maps, and GPS	• Reduces nitrogen fertilizer over-application • Minimizes nitrous oxide emissions • Optimizes chemical inputs	• Fertilizer management • Pesticide optimization • Seed placement • Slurry application	• Lower GHG emissions • Reduced input waste • Targeted spatial applications	Pawase et al. (2023)
Smart Sensors and IoT	Real-time monitoring systems integrated with Internet of Things	• Prevents over-fertilization • Optimizes irrigation timing • Monitors emission levels	• Soil moisture sensors • Nutrient sensors • Weather stations • Gas emission sensors	• Reduced water waste • Precise nutrient management • Real-time emission tracking	Nuwarapaksha et al. (2025)
Remote Sensing and Satellites	Satellite imagery, aerial photography, and spectral analysis	• Tracks carbon sequestration • Monitors vegetation cover • Measures soil organic carbon	• Carbon monitoring • Biomass assessment • Crop health analysis • Large-scale monitoring	• 10,000× faster than traditional models • Cost-effective monitoring • Accurate carbon tracking	Angelopoulou et al. (2019)
AI and Machine Learning	Advanced computational models for agricultural optimization	• Predicts optimal application timing • Quantifies GHG emissions • Optimizes resource use	• Emission tracking • Predictive analytics • Pattern recognition • Decision support systems	• Real-time emission quantification • Improved decision-making • Efficient resource management	Hasan et al. (2025)

Source: Authors' compilation based on data from Angelopoulou et al. (2019); Hasan et al. (2025); Nuwarapaksha et al. (2025); Pawase et al. (2023).

Table 3. Use of best agronomic practices in the real world.

Specific Strategies Used for Mitigating Climate Change Impacts	Location	Main Findings of the Experiments	References
Crop rotation with cover crops	Texas High Plains	Net GHG emissions fell by 40% in improved rotations vs. conventional farming. Direct on-farm carbon footprint dropped 50% by mid-century in this model.	Attia et al. (2025)
Agroforestry systems with coffee plantations	The Southeast Mountains region, Brazil	The study region's annual mean air temperature is predicted to rise by 1.7 °C ± 0.3 by 2050. This will result in an almost 60% decrease in the area that may be used for coffee production in unshaded plantations. By 2050, however, agroforestry systems with 50% shade cover can lower mean temperatures and keep 75% of the land usable for coffee production.	Gomes et al. (2020)
Agroforestry systems with trees and cereals	Central Punjab, Pakistan	The amount of carbon in agroforestry land use systems was found in the order of boundary planting system > scattered planting system > bund planting system > agri-horti system > agricultural system (only crop). The C stock (42.77 t ha^{-1}) increased by 49.51%, 20%, 82%, and 361% in the boundary planting system compared to the bund, scattered, agri-horti, and sole cropland, respectively.	Yasin et al. (2023)
Reduced tillage in organic farming	Switzerland, Germany, France, and The Netherlands	Reduced tillage in comparison with plowing increased organic carbon stocks in the surface soil layer (0–15 cm) by 20.8%, depleted in the intermediate soil layers to 50 cm soil depth with a maximum depletion of 6.6% cm and increased in the deepest (70–100 cm) soil layer by 14.4%.	Krauss et al. (2022)
Advanced nutrient (nitrogen) application	China	The results showed that, compared with all normal urea as base fertilizer, controlled-release urea and split application of normal urea increased crop yield by 10.08% and 8.11%, respectively, and N use efficiency by 47.55% and 45.21%, respectively.	Zhang et al. (2022)

Source: Authors' compilation based on data from Attia et al. (2025); Gomes et al. (2020); Krauss et al. (2022); Yasin et al. (2023); Zhang et al. (2022).

10. Challenges to Adopt Agronomic Practices

Adapting good agricultural techniques is recognized as an important climate change mitigation option for safeguarding future food security and farmer livelihoods (Vermeulen et al. 2012). However, numerous social, economic, educational, and institutional barriers exist to the successful adaptation of climate-smart agronomic best practices.

Key constraints include a lack of access to financial resources for farmers to implement new management strategies, inefficient agricultural extension services that fail to transfer updated climate knowledge to farmers, and a lack of institutional support mechanisms that incentivize the adoption of adaptive practices (Tigchelaar et al. 2018). Additionally, the site-specificity of climate impacts and vulnerability creates difficulties in developing universally applicable adaptation recommendations (Vermeulen et al. 2012). There are also scaling difficulties moving from controlled research plots to diverse real-world landscapes, as well as long time lags between adaptation actions and observable impacts in agroecosystems. Furthermore, there is no common technique for climate-resilient agronomic management practice, and farming techniques and geographical locations will all influence the successful application of appropriate agronomic approaches. Comprehensive research is required to prevent trade-offs and maladaptation of various agronomic methods. When it comes to the successful adoption of precision agriculture technologies for climate mitigation, it faces several key challenges that require strategic solutions. Initial investment represents a significant barrier, as the high upfront costs for sensors and equipment can deter farmers from adopting these technologies, particularly smaller operations with limited capital resources (Getahun et al. 2024). Equally important is the need for robust data management systems that can effectively collect, store, and analyze the vast amounts of information generated by precision agriculture tools, requiring both technological infrastructure and organizational capacity. Technical expertise presents another crucial consideration, as farmers and agricultural professionals need comprehensive training to effectively implement and operate these sophisticated systems, from understanding sensor calibration to interpreting data outputs for decision-making.

Overcoming these barriers will require integrated approaches between researchers, extension services, farmers, communities, and policymakers. More agro-climate decision-making tools need to be developed with farmer participation to enable context-specific adaptation pathways (Vermeulen et al. 2012). Strengthening local adaptive capacity, along with expanding insurance, credit, and social safety nets, is also critical to facilitating the adoption of adaptive best practices (Wheeler

and von Braun 2013). Success will depend on tailored, localized solutions that make agronomic innovations accessible and beneficial at the farmer scale.

The evolution of precision agriculture for climate mitigation is moving toward enhanced AI capabilities that will provide more sophisticated predictive models, enabling farmers to anticipate and respond to climate-related challenges with greater precision and effectiveness. Simultaneously, improved sensor technology is advancing toward more accurate and cost-effective monitoring solutions that will make precision agriculture accessible to a broader range of agricultural operations while providing more detailed environmental data. The development of integrated platforms represents perhaps the most transformative future direction, promising seamless data flow between different technologies to create comprehensive farm management systems that optimize both productivity and climate mitigation outcomes through coordinated, intelligent decision-making processes. As an example, Sinore and Wang (2024) identified that communities and governments in Ethiopia have developed adaptation and mitigation plans that include mixed farming, land management, and diversification of sources of income. It is crucial to develop an equitable and inclusive strategy that involves all parties involved, especially women, young people, and marginalized communities, to improve climate resilience. Decision makers in the fields of agriculture, microfinance, and meteorology should guarantee farmers' access to credit and climate data in order to accomplish this, successfully overcoming knowledge gaps and financial limitations.

11. Conclusions

The adoption of sustainable agronomic techniques has great potential to position agriculture as a key accelerator for climate change mitigation and adaptation. This chapter underscores the transformative impact of techniques such as conservation tillage, permanent soil cover, crop diversification, agroforestry, organic farming, improved livestock management, soil health enhancement, carbon farming, and precision agriculture. These sustainable agricultural practices contribute significantly to SDG 13 (Climate Action) through multiple mechanisms that reduce greenhouse gas emissions, enhance carbon sequestration, and improve climate resilience. The adoption of the best agronomic practices plays a pivotal role in achieving Sustainable Development Goal 13, which calls for urgent action to combat climate change and its impacts. Key findings suggest that while several practices offer substantial benefits, their effectiveness is context-specific and often limited by socio-economic and institutional factors. Therefore, integrated and localized approaches are essential for scaling up sustainable agronomic interventions.

The scientific consensus, coupled with a growing body of practical experience, underscores the urgency and feasibility of scaling sustainable agronomy on a global scale. Through dedicated collaboration among farmers, policymakers, scientists, and stakeholders, agriculture can fully realize its momentous potential as a central pillar of climate action. By committing to these sustainable practices, the agriculture sector not only addresses environmental challenges but also becomes a proactive force in shaping a resilient and sustainable future for our planet.

The evolution of precision agriculture for climate mitigation is moving toward enhanced AI capabilities that will provide more sophisticated predictive models, enabling farmers to anticipate and respond to climate-related challenges with greater precision and effectiveness. Simultaneously, improved sensor technology is advancing toward more accurate and cost-effective monitoring solutions that will make precision agriculture accessible to a broader range of agricultural operations while providing more detailed environmental data. The development of integrated platforms represents perhaps the most transformative future direction, promising seamless data flow between different technologies to create comprehensive farm management systems that optimize both productivity and climate mitigation outcomes through coordinated, intelligent decision-making processes.

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Climate Change Perception and Adaptation Behaviours Among Root and Tuber Crop Farmers: Towards Improving Climate Action in Agriculture

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1. Introduction

1.1. Overview

The discourse on climate change is heavily supported by scientific evidence that human activities, particularly since the industrial revolution, have significantly altered the Earth's atmosphere (Habibullah et al. 2022; Hamza et al. 2020). The burning of fossil fuels and extensive land-use changes have led to increased concentrations of greenhouse gases, particularly carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (MacCarthy et al. 2018). These gases trap heat within the atmosphere, intensifying the greenhouse effect and leading to a gradual but steady rise in global temperatures (MacCarthy et al. 2018). The Intergovernmental Panel on Climate Change (IPCC 2014) warns that these temperatures could exceed 1.5 °C in the coming decades, a scenario that spells dire consequences for global ecosystems and human livelihoods (Pörtner et al. 2022). For Small Island Developing States, like Trinidad and Tobago, climate projections are particularly alarming, with temperature increases between 2.4 and 3.6 °C expected by 2100 (Mycoo and Roopnarine 2024). This is to be accompanied by a decrease in rainfall of 22–30% and a significant rise in sea levels (Mycoo and Roopnarine 2024). Such changes can result in more frequent and severe weather events like storms (Mycoo and Roopnarine 2024; Roopnarine et al. 2021). The situation in Trinidad and Tobago exemplifies some of the international challenges faced due to climate change and reflects broader global concerns, particularly for food security (Dawson et al. 2016).

As global temperature rises, the susceptibility of agricultural systems to climate-induced stresses increases, jeopardizing food production and availability, especially in regions like Africa, South Asia, and small island states including those in the Caribbean (Pörtner et al. 2022; Kogo et al. 2021). The potential for a 2 °C rise in surface temperatures could drastically impact terrestrial and aquatic food production

systems, leading to reduced soil nutrition, increased food prices, disrupted growing seasons, a loss of cropland, and diminished agricultural output (Gomez-Zavaglia et al. 2020; Connolly-Boutin and Smit 2016). In this challenging context, Trinidad and Tobago, like other nations, confronts the dual task of adapting to inevitable changes while actively participating in global efforts to mitigate impending climate impacts. Climate action is therefore critical.

As such, the Government of Trinidad and Tobago has acknowledged the need to adopt mitigation strategies against climate change as a critical component to the future development of the agriculture sector (Ministry of Planning and Development 2019). The implementation of climate mitigation strategies in agriculture requires collaboration with key stakeholders, particularly farmers who are among the first to observe and respond to these changes. A review of the literature indicates a need to not only look at adaptive measures of and in themselves but to consider the human element in adaptation at the level of the rural community and farmers specifically (Barrett et al. 2024; Shah et al. 2020; Connolly-Boutin and Smit 2016). Thus, climate change adaptation measures in agriculture lessen the impact of climate change and the resultant effects on farmers (Virgil and Pun 2023). However, farmers' initial perception of climate change and adaptation measures pursued are not always straightforward or predictable (Barrett et al. 2024; Virgil and Pun 2023; Connolly-Boutin and Smit 2016). Specifically, farmers' perception of climate change refers to the subjective beliefs and understandings that farmers have about the occurrence and impacts of climate change. Therefore, there is a need for integrated people-centred agricultural strategies that address the intersecting challenges of climate change, ecological conservation, and sustainable development, as articulated in the Sustainable Development Goals (SDGs) adopted by the United Nations (UN) in 2015 (UN 2015).

1.2. Climate Change in the Context of the Development Goals

1.2.1. The UN SDGs and Their Local Context

In 2015, the United Nations established 17 SDGs, building on the Millennium Development Goals (MDGs) (UN 2015, 2017). These goals represent a holistic framework aimed at addressing the environmental, social, and economic challenges facing the globe (Beckmann 2024; UN 2015, 2017). For Small Island Developing States (SIDSs) like Trinidad and Tobago, the SDGs are particularly critical as they address the acute vulnerabilities these nations face due to climate change (Mycoo and Roopnarine 2024; UN 2012). Despite global efforts, progress towards the 17 SDGs and their related 169 targets set for 2030 has been uneven, with SIDSs at a particular

disadvantage due to inherent challenges such as limited size, geographic isolation, resource constraints, and susceptibility to economic shocks (Mycoo and Roopnarine 2024; UN 2012).

Locally, Trinidad and Tobago's national development strategies, as encapsulated in the Vision 2030 plan (GORTT 2016), align closely with these global targets. This plan emphasizes environmental sustainability and people-centric development as fundamental to the nation's progress (GORTT 2016). Additionally, these themes are echoed in the United Nations Multi-Country Sustainable Development Cooperation Framework (MSDCF) for the English and Dutch-speaking Caribbean (2022–2026), which highlights priorities like climate resilience, economic prosperity, and social equality (UN Caribbean 2022). Considering the ongoing impacts of COVID-19 and the need for resilient recovery, the MSDCF serves as a strategic guide for implementing SDGs in the Caribbean region, where Trinidad and Tobago is situated (UN Caribbean 2022).

Additionally, the need to enhance food security among SIDSs was emphasized at the fourth International Conference on Small Island Developing States (SIDS4) hosted in Antigua and Barbuda. It concluded with a declaration (UN 2024), which contained a three-point methodology for enhancing food security by focusing on:

- The development and implementation of adaptation/mitigation strategies that consider the linkages between food, water, and energy;
- Increasing sustainable agriculture, food security, nutrition, and livelihood to assist with climate adaptation;
- The promotion and acceleration of the achievement of sustainable agricultural practices that are climate-resilient.

This declaration of intent emphasizes the urgency for climate action and supports the mandate of SDG 13—climate action.

1.2.2. Transitioning to Climate Action—SDG 13

SDG 13, which calls for urgent actions to combat climate change and its impacts, consists of five targets that revolve around building climate resilience, creating climate policies, and improving climate knowledge (UN 2015). Climate action is pivotal for all countries, especially SIDSs, in the Pacific and Caribbean, as it directly influences their survival and sustainable development. For example, in Trinidad and Tobago, climate change has resulted in increased flooding and droughts, which cause damage to irrigation lines and water tanks used by farmers, increased water turbidity, and a reduction in the availability of fresh water through salinization and resource

depletion (Mycoo and Roopnarine 2024; Roopnarine et al. 2021). This, in turn, has dire consequences for agriculture, human health, and overall economic stability.

Addressing these challenges requires a robust commitment to SDG 13. Climate action not only supports the sustainability of natural resources and economic systems but also ensures the resilience and well-being of communities in the face of escalating climate challenges. By enhancing climate resilience, nations around the world can mitigate the adverse effects of climate change while supporting sustainable agricultural practices and food security.

1.3. Climate Change in the Context of Agricultural Production

Climate change is increasingly recognized as a significant threat to global food security, disproportionately affecting low-income countries that are particularly vulnerable to rising temperatures and water scarcity (Kogo et al. 2021). Such environmental stressors exacerbate food insecurity and have the potential to increase poverty levels with broader economic impacts, including higher food prices and reduced agricultural diversity. These changes are expected to affect various regions worldwide, notably Africa, South Asia, and Caribbean small island states (Pörtner et al. 2022; Kogo et al. 2021), where the dependence on agriculture for livelihoods is significant.

In 2022, the Caribbean Community (CARICOM) started the 'Vision 25% by 2025' initiative to reduce the food import bill by 25% by 2025 (CARICOM 2024). The target date was extended by an additional five years to 2030 (CARICOM 2025). The initiative aims to enhance local agricultural production by focusing on priority crops such as root and tuber crops, which are essential for both food security and economic stability in the Caribbean region (CARICOM 2024).

1.4. Climate Change's Impact on Root and Tuber Crop Production

Root and tuber crops are staple foods that are cultivated on approximately 50 million hectares worldwide, a substantial portion of which is in developing countries (Allemann et al. 2004). Their low labour requirements and the ability to be stored in-ground provide a form of resilience against food shortages, making their sustainable production crucial amidst the growing pressures of climate change, rural poverty, and environmental stresses (Allemann et al. 2004). In Trinidad and Tobago and other Caribbean SIDSs, the cultivation of root and tuber crops like yam (*Dioscorea* spp.), cassava (*Manihot esculenta* Crantz), sweet potatoes (*Ipomoea batatas* (L.) Lam.), dasheen (*Colocasia esculenta* var esculenta (L.) Schott), eddoes (*Colocasia esculenta* var antiquorum Schott), potatoes (*Solanum tuberosum* (L.), and

tannia (*Xanthosoma sagittifolium* (L.) Schott) is recognized as a vital component of food security (Harrynanan et al. 2015). These crops are not only essential staples but also hold significant economic importance in rural communities, providing both nutritional and financial stability (Allemann et al. 2004). The resilience of root and tuber crops to marginal growing conditions makes them invaluable in areas facing adverse climatic changes which deter food production and disrupt local and regional economies (Limisha and Swadija 2023). Ganpat and Isaac (2015) offer a detailed analysis of how climate change impacts food availability, accessibility, and stability in these vulnerable regions. Climatic shifts, higher temperatures, altered precipitation patterns, and extreme weather events disrupt crop cycles, reduce yields, and heighten pest and disease outbreaks (Allemann et al. 2004). The Intergovernmental Panel on Climate Change (IPCC 2014) notes significant risks to food security, predicting declines in crop productivity in many tropical and subtropical regions due to warming and erratic rainfall. These threats underscore the importance of addressing the impacts of climate change on root and tuber crops. The increasing global temperatures severely affect the growth and yield of root and tuber crops (Ganpat and Isaac 2015). Moreover, it was stated that the agricultural production for root crops will be adversely affected by the temperature increases and lower rainfall projected through to 2050 in Trinidad and Tobago (Ministry of Planning and Development 2019). Rising temperatures, for example, disrupt the sprouting and establishment phases, inhibit seed germination, and delay sprout emergence, which can severely affect crop establishment and reduce yields. Additionally, higher temperatures accelerate crop developmental stages, leading to shorter growth cycles and smaller tubers, thus decreasing their marketable yield and economic value (Lal et al. 2022). Such temperature increases also exacerbate water stress, particularly in areas already facing water scarcity. This leads to smaller tubers and potential crop failures. Sweet potatoes, in particular, are vulnerable, with potential yield reductions of up to 27% under increased-temperature conditions (Kimball 2016). Temperature thresholds are crucial in determining the yields of root and tuber crops, as each type has specific temperature requirements for optimal growth. Furthermore, understanding these thresholds is essential for assessing the potential impacts of temperature fluctuations on the productivity of these crops (Raza et al. 2019; Brown et al. 2016). For example, cassava shows optimal growth within a temperature range of 25 °C to 32 °C, with yields declining outside this range (Brown et al. 2016). Climate change impacts also increase the prevalence of diseases and pests among root and tuber crops hampering crop production (Allemann et al. 2004). For example, in Southern Africa, stem elongation and the African Cassava Mosaic Disease (CMD)

severely reduces cassava yields. At the same time, sweet potato production is frequently affected by viruses and weevils (Allemann et al. 2004). These challenges not only threaten crop yields but also the genetic diversity essential for the crops' adaptation to changing environmental conditions. All these adverse effects pose significant threats to food security by potentially increasing food prices and limiting access to adequate food supplies.

1.5. Climate Change Adaptation in Root and Tuber Crop Production

The need for adaptation strategies in agriculture has become increasingly urgent as climate change continues to impose significant challenges on global food systems, particularly in developing regions (Saravanan and Gutam 2023). To combat these issues, innovative adaptation strategies are being implemented by root and tuber crop farmers in the Caribbean (Witkowski and Medina 2017; Tandon and Palacios 2014). These include the following:

1. The adoption of new varieties that are more resistant to diseases and pests. Biotechnological advances such as genetic engineering have facilitated the development of these varieties, enhancing their resilience to climatic stresses.
2. The use of in vitro gene banking and meristem cultures to produce virus-free plants, which are crucial for maintaining healthy crops and ensuring yield stability.
3. The recommendation that changes in rainfall patterns necessitate efficient water use. Farmers are adopting rainwater harvesting and drip irrigation systems to optimize water use and minimize the impact of drought conditions.
4. The use of an integrated approach using biological, physical, and chemical pest management techniques to tackle infestations of pests and disease that are environmentally sustainable and economically viable.
5. The incorporation of trees into their farming systems to provide shade, reduce soil erosion, and improve soil fertility, which in turn supports the growth of root and tuber crops under changing climatic conditions.

By integrating traditional agricultural knowledge with modern scientific innovations, Caribbean farmers can enhance the resilience of their root and tuber crops to climatic changes and also secure food sources for some of the world's most vulnerable populations. Advances in biotechnology and precision agriculture, including genetic engineering, molecular marker technology, and improved crop production techniques, offer promising solutions to these challenges to improving agricultural resilience towards addressing the objectives of food security and sustainable development. These technological innovations are crucial in regions faced with the dual challenges of climatic adversity and economic limitations,

highlighting the urgent need for robust, resilient agricultural systems that can sustain not only the livelihoods of farmers but also global food security (Gebbers and Adamchuk 2010). Also, this highlights the critical importance of continued research and development in this area, ensuring that adaptation strategies evolve in line with changing environmental realities.

1.6. Gaps in Information and Need for This Research

The global agricultural sector is in a period of significant transition due to climate variability, with root and tuber crop production facing unique challenges and opportunities due to their specific vulnerabilities (Raymundo et al. 2018). Despite their resilience to adverse conditions and their crucial role in food security, the adaptation strategies adopted by root and tuber crop farmers, especially smallholders, are poorly documented. This gap in knowledge hinders the formulation of targeted policies and interventions needed to support this vital agricultural sector. The existing scientific literature has limited studies that are focused on the direct impacts of climate change on root and tuber crop production (Porter et al. 2021). Many studies generalize vulnerabilities and adaptations across broad agricultural categories, neglecting the unique physiological and agronomic characteristics of root and tuber crops (Hijmans 2003). Furthermore, the socio-economic factors influencing farmers' decisions on adaptation strategies, such as resource availability, access to technology, and extension services, are not sufficiently explored. By extension, considering the socio-cognitive processes which underpin farmers' decisions to adapt their agricultural practices because of climate change impacts are beneficial (Mitter et al. 2019). There is a need to fill the existing information gaps by conducting an in-depth analysis of the perception of climate change among root and tuber crop farmers as well as an evaluation of their adaptation measures. Farmers' perception of climate change refers to the subjective beliefs and understandings that farmers have about climate change occurrence and impacts. Therefore, the objective of this study was to evaluate the perception and adaptation behaviours of root and tuber crop farmers towards climate change. By focusing on Trinidad and Tobago, this study will provide detailed insights into farmers' views of local climate change impacts and their coping strategies. The anticipated outcomes will contribute to the understanding of agricultural resilience in the face of climate change and help inform policy decisions that enhance the sustainability of root and tuber crop production globally.

2. Methodology

2.1. Area of Study

This study was conducted in the Republic of Trinidad and Tobago, a twin island archipelagic state in the southern Caribbean, located 10° N to 11.5° N latitude and 60° W to 62° W longitude, which lies just 11 km off the coast of north-eastern Venezuela and 130 km south of Grenada (Figure 1). Trinidad and Tobago experiences a tropical climate characterized by a distinct dry season from January to May and a wet season for the remainder of the year.

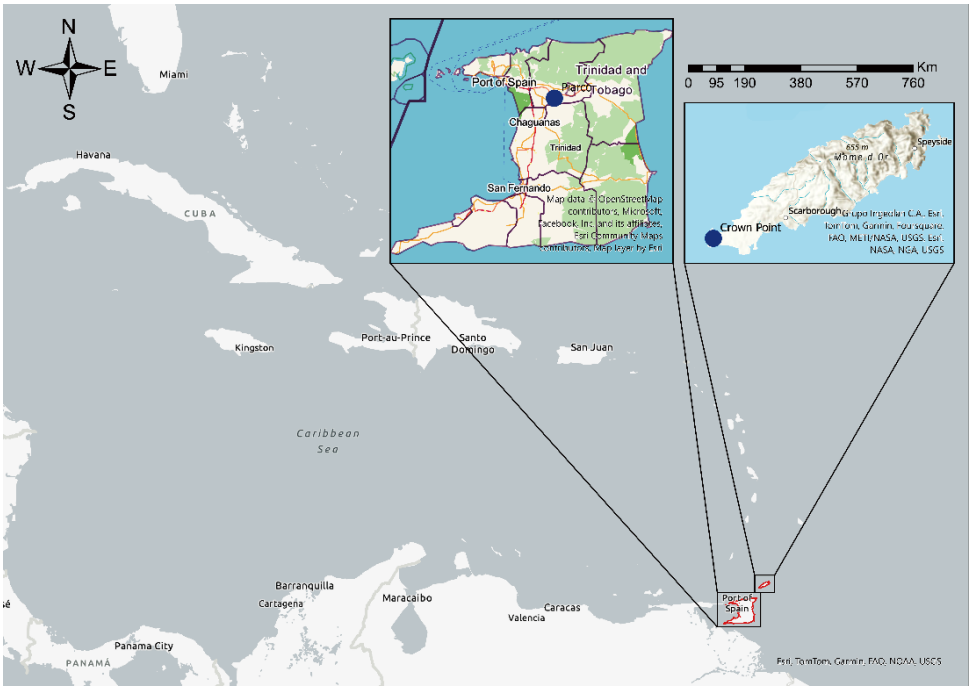


Figure 1. Map of the Caribbean highlighting Trinidad and Tobago and the two cities (Piarco and Crown Point) where meteorological data were collected. Source: Figure by authors.

2.2. Study Design and Participants

A survey was conducted using a structured pre-tested questionnaire and both on-line and face-to-face distribution methodologies between 31 January and 29 April 2022, to investigate perception towards climate change and its impact on root and

tuber crop production among farmers in Trinidad and Tobago. Socio-demographic and background variables were also collected via the questionnaire. Each participant that was selected had to be actively producing one or more of the following root and tuber crops within the last year leading up to this study: yam (*Dioscorea* spp.), cassava (*Manihot esculanta*), sweet potato (*Ipomoea batatas*), dasheen (*Colocasia esculenta* var. esculenta), eddoes (*Colocasia esculenta* var. antiquorum), potatoes (*Solanum tuberosum*), and tannia (*Xanthosoma sagittifolium*). For face-to-face distribution, interviewers with prior survey experience read the questions to respondents and entered responses directly into Google Forms using a tablet or cellular phone.

2.3. Data Collection

An initial list of potential respondents with their locations and contact information was prepared in collaboration with extension officers from the Ministry of Agriculture, Land and Fisheries (MALF), local agro-input suppliers, and academics involved in teaching agriculture. Respondents were contacted either online or face-to-face to complete the structured questionnaire. For online distribution, the survey link was shared using various crowdsourcing approaches including direct emails and social media. For both online and face-to-face distribution, convenience sampling and snowball sampling methods were also used where participants not only completed the questionnaire but referred other farmers to help recruit a large sample and ensure the wide distribution of the survey. The questionnaire was completed anonymously with prior informed consent by respondents, who were informed that they could discontinue participation in the survey at any time. The participants were given no financial reward or other incentives for participation.

2.4. Measures

2.4.1. Socio-Demographic and Background Variables

Twelve socio-demographic variables were collected, including age category, sex, the highest education level attained, combined monthly household income (in USD), the status of farming as a main source of income, household size (the number of members living in the household), farming experience, land ownership, farm size, farmer registration status, the frequency of extension visits received, and access to finance. Farmers were asked to indicate the type of root and tuber crops produced.

2.4.2. Likert Scale Responses

Additional questions asked respondents to give responses to statements geared toward determining their attitude and perception towards climate change and its possible impact on root and tuber crop production in Trinidad and Tobago. These responses were based on a four-point Likert scale. For 'farmers' perception of the frequency of climate-related outcomes affecting farms', and 'farmers' perception of the severity of impacts associated with climatic change', the Likert scale descriptor was 1 (no impact), 2 (low impact), 3 (moderate impact), or 4 (high impact). For 'farmers' perception of the intensity of climatic events affecting farms', the Likert scale descriptor was 1 (no change), 2 (decreasing), 3 (increasing), or 4 (unsure).

2.5. Coding and Data Analysis

Data obtained from the survey were numerically coded and then subjected to both descriptive and inferential statistical analysis. Overall perception scores for respondents were determined by using total scores. In turn, the total scores were obtained by summating the scores of all statements within respective sections as follows:

- For the section on 'farmers' perception of the frequency of climate-related outcomes affecting farms', responses to statements (n = 7) were scored as follows: 1 (no impact), 2 (low impact), 3 (moderate impact), or 4 (high impact). The scores were combined to give a score range of 7–28.
- For the section on 'farmers' perception of the intensity of climatic events affecting farms', responses to statements (n = 4) were scored as follows: 1 (no change), 2 (decreasing), 3 (increasing), or 4 (unsure). The scores were combined to give a score range of 4–16.
- For the section on 'farmers' perception of the severity of impacts associated with climatic change', responses to statements (n = 8) were scored as follows: 1 (no impact), 2 (low impact), 3 (moderate impact), or 4 (high impact). The scores were combined to give a score range of 8–32.

Next, overall scores in each section were tallied for descriptive purposes and to operationalize each variable. Binary logistic regression analyses were performed to predict which socio-demographic characteristics were associated with farmers' adoption of coping and adaptation measures to climate change's impacts on root and tuber crop production in Trinidad and Tobago. One-way analysis of variance (ANOVA) tests and associated post hoc tests (Tukey's b) were performed using the total tallied score for each respondent, in order to examine significant

differences among mean score for perceptions, with the socio-demographic factors as independent variables. Spearman's rank-order correlation coefficients were calculated to examine the interrelationships among the socio-demographic factors to select factors for further analysis. All statistical analyses were performed using the Statistical Package for Social Sciences software (SPSS v. 28).

3. Results

3.1. Socio-Demographics Characteristics of Respondents

The socio-demographic characteristics of the respondents are presented in Table 1. The age category with the most significant number of respondents was 45–64 years (46.3%), followed by 25–44 years (34.1%). Most respondents were male (84.1%). The distribution of respondents by educational level indicated that 32.9% attained secondary education, 20.7% attained primary education, 25.6% attained tertiary education, 12.2% had no formal education, and 8.5% had vocational training. More than half of the respondents relied on farming as their primary source of income (58.5%), were registered with the government or state agency (76.8%), and had access to finance for farming (61%).

Table 1. Socio-demographic characteristics of farmers in the survey (n = 82).

Socio-Demographic Categories	Description	Frequency	Farmers % (n = 82)
Age	<25	6	7.3
	25–44	28	34.1
	45–64	38	46.3
	>64	10	12.2
Sex	Male	69	84.1
	Female	13	15.9
Education level	Primary school	17	20.7
	Secondary school	27	32.9
	Vocational training	7	8.5
	Tertiary	21	25.6
	No formal education	10	12.2

Table 1. *Cont.*

Socio-Demographic Categories	Description	Frequency	Farmers % (n = 82)
Combined monthly household income (USD)	<1001	13	15.9
	1001–2500	37	45.1
	2501–5000	17	20.7
	5001–10,000	10	12.2
	>10,000	5	6.1
Farming as main source of income	No	34	41.5
	Yes	48	58.5
Household size (members)	Less than 5	51	62.2
	5–10	28	34.1
	More than 10	3	3.7
Experience in farming (years)	<5	13	15.9
	5–10	17	20.7
	11–15	23	28
	16–20	15	18.3
	>20	14	17.1
Land ownership	Personal ownership	21	25.6
	Family ownership	20	24.4
	Private rent/lease	12	14.6
	Govt. rent/lease	14	17.1
	Squatting	15	18.3
Farm size (hectares)	<2	32	39
	2–5	16	19.5
	5–10	19	23.2
	>10	15	18.3
Farmers' registration status	Not registered	19	23.2
	Registered	63	76.8

Table 1. *Cont.*

Socio-Demographic Categories	Description	Frequency	Farmers % (n = 82)
Frequency of extension visits	Weekly	3	3.7
	Monthly	22	26.8
	Quarterly	18	22
	Semi-annually	15	18.3
	Annually	2	2.4
	Never	22	26.8
Access to finance	No	32	39
	Yes	50	61

Source: Table by authors.

3.2. Root and Tuber Crops Produced

The farmers in the survey produced a range of root and tuber crops (Table 2, Figure 2). The most common root and tuber crop produced among farmers was sweet potato, with 56.1% of the farmers growing this crop. This was followed by 39% of the farmers producing cassava. The root and tuber crop produced by the least number of farmers in this study was tannia at 2.4% and then potato at 7.3% of the participants. Most farmers (65.8%) produced only a single root and tuber crop, while others produced two or more of the focus crops in this study.

Table 2. Root and tuber crops produced and frequency among respondents in this study.

Crops Produced	Frequency	Farmer % (n = 82)
Sweet potato	46	56.1
Cassava	32	39
Eddoes	21	25.6
Dasheen	15	18.3
Yam	8	9.8
Potato	6	7.3
Tannia	2	2.4

Source: Table by authors.



Figure 2. Some of the root and tuber crops produced by farmers in this survey: (**A**) sweet potato (*Ipomoea batatas*); (**B**) cassava (Manihot esculenta); (**C**) eddoes (*Colocasia esculenta* var. antiquorum); (**D**) potato (*Solanum tuberosum*); (**E**) yam (*Dioscorea* spp.); (**F**) dasheen/taro (*Colocasia esculenta* var. esculenta). Source: Authors' compilation based on images from Pexels.com.

3.3. Farmers' Perception of the Frequency of Climate-Related Outcomes Affecting Farms

The farmers' perceptions of the frequency of climate-related outcomes affecting their farms are shown in Figure 3. Overall, mean perceptions indicated that 36.9% of the root and tuber crop farmers perceived the frequency to be of low impact, 34.5% of moderate impact, 21.9% of no impact, and 6.6% of high impact. Therefore, 78.1% of the farmers reported that they perceived climate-related outcomes as affecting their farm. When assessing the climatic outcomes individually, pest and disease proliferation had the highest level of responses for high and moderate impact with 11% and 51.2%, respectively. It also had the lowest level of responses for low impact (2.4%) (Figure 3). The respondents' mean perception score of the frequency of climate-related outcomes affecting their farms was statistically significant for the socio-demographic factors of education level ($p = 0.032$), combined monthly household income ($p < 0.001$), and household size ($p < 0.001$) (Table 3). Respondents with secondary school education had the highest mean perception score (17.074 ± 0.645), which was significantly greater than that of respondents who received no formal education (13.100 ± 1.060) (Table 3).

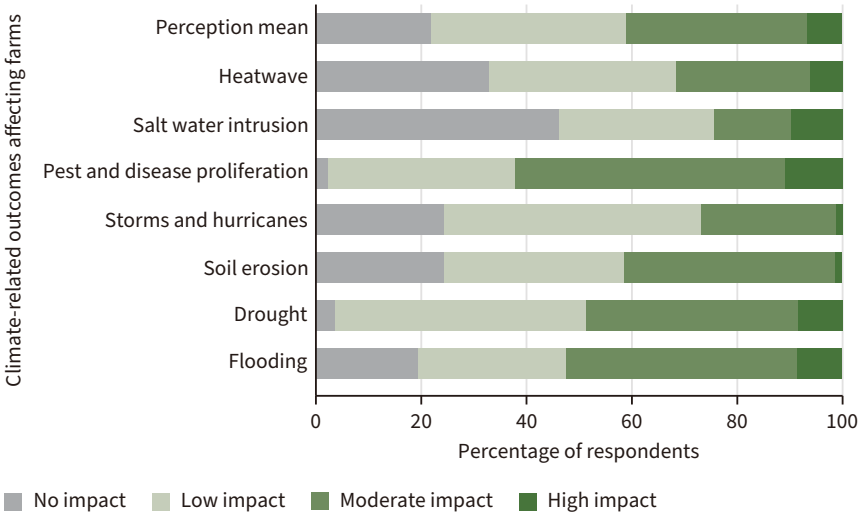


Figure 3. Farmers' perception of the frequency of climate-related outcomes affecting farms. Source: Figure by authors.

Table 3. ANOVA model of the socio-demographic variables in farmers' perception of climate change and its impacts.

Socio-Demographic Categories	Description	Farmers' Perception of Climate Change		
		Frequency (Mean ± SEM)	Intensity (Mean ± SEM)	Severity (Mean ± SEM)
Age	<25	15.500 ± 1.436	7.500 ± 0.495	21.167 ± 1.532
	25–44	15.536 ± 0.665	8.821 ± 0.229	20.643 ± 0.709
	45–64	16.342 ± 0.571	8.368 ± 0.197	20.789 ± 0.609
	>64	14.700 ± 1.112	8.000 ± 0.383	21.900 ± 1.187
	F value	0.694	2.602	0.302
	p-value	0.558	0.058	0.824
Sex	Male	15.696 ± 0.423	8.377 ± 0.151	20.725 ± 0.446
	Female	16.385 ± 0.974	8.615 ± 0.347	21.846 ± 1.027
	F value	0.421	0.398	1.003
	p-value	0.518	0.53	0.32
Highest education level attained	Primary school	16.176 ± 0.813 ab *	8.176 ± 0.306	21.412 ± 0.879
	Secondary school	17.074 ± 0.645 a	8.370 ± 0.243	21.556 ± 0.698
	Vocational training	15.286 ± 1.267 ab	8.857 ± 0.477	20.286 ± 1.370
	Tertiary	15.333 ± 0.732 ab	8.381 ± 0.275	21.190 ± 0.791
	No formal education	13.100 ± 1.060 b	8.700 ± 0.399	18.100 ± 1.147
	F value	2.793	0.506	1.88
	p-value	0.032	0.731	0.122
Combined monthly household income (USD)	<1001	13.385 ± 0.883 bc	7.846 ± 0.346	18.923 ± 0.99
	1001–2500	16.432 ± 0.524 ab	8.622 ± 0.205	21.270 ± 0.587
	2501–5000	17.706 ± 0.772 a	8.471 ± 0.303	22.471 ± 0.866
	5001–10,000	15.000 ± 1.007 abc	8.400 ± 0.394	20.700 ± 1.129
	>10,000	12.600 ± 1.424 c	8.400 ± 0.558	18.400 ± 1.597
	F value	5.177	0.975	2.538
	p-value	<0.001	0.426	0.071

Table 3. *Cont.*

Socio-Demographic Categories	Description	Farmers' Perception of Climate Change		
		Frequency (Mean ± SEM)	Intensity (Mean ± SEM)	Severity (Mean ± SEM)
Main source of income	Farming	15.382 ± 0.600	8.500 ± 0.215	20.765 ± 0.639
	Non-farming activities	16.104 ± 0.505	8.354 ± 0.181	21.000 ± 0.538
	F value	0.846	0.27	0.079
	p-value	0.36	0.605	0.779
Household size (members)	Less than 5	14.627 ± 0.446 b	8.314 ± 0.176	19.725 ± 0.479 b
	5–10	17.643 ± 0.602 ab	8.571 ± 0.237	22.893 ± 0.646 a
	More than 10	18.667 ± 1.838 a	8.667 ± 0.725	22.333 ± 1.974 ab
	F value	9.362	0.444	8.029
	p-value	<0.001	0.643	0.001
Experience in farming (years)	<5	14.231 ± 0.951	8.769 ± 0.343	19.077 ± 1.015
	5–10	16.529 ± 0.831	8.294 ± 0.300	21.824 ± 0.887
	11–15	16.870 ± 0.715	8.739 ± 0.258	21.435 ± 0.763
	16–20	15.800 ± 0.885	8.200 ± 0.319	21.467 ± 0.945
	>20	14.643 ± 0.916	7.929 ± 0.330	20.000 ± 0.978
	F value	1.832	1.359	1.502
	p-value	0.131	0.256	0.21
Land tenure	Personal ownership	15.429 ± 0.767	8.619 ± 0.275	20.095 ± 0.820
	Family ownership	17.000 ± 0.785	8.450 ± 0.281	21.100 ± 0.840
	Private rent/lease	15.750 ± 1.014	8.667 ± 0.363	21.167 ± 1.085
	Govt. rent/lease	15.071 ± 0.939	8.214 ± 0.336	20.786 ± 1.004
	Squatting	15.467 ± 0.907	8.067 ± 0.325	21.667 ± 0.970
	F value	0.827	0.639	0.43
	p-value	0.512	0.637	0.787

Table 3. *Cont.*

Socio-Demographic Categories	Description	Farmers' Perception of Climate Change		
		Frequency (Mean ± SEM)	Intensity (Mean ± SEM)	Severity (Mean ± SEM)
Farm size (ha)	<2	15.531 ± 0.608	8.594 ± 0.222	20.469 ± 0.649
	2–4	15.250 ± 0.860	8.188 ± 0.314	20.625 ± 0.918
	5–10	17.421 ± 0.789	8.474 ± 0.288	22.421 ± 0.843
	>10	14.933 ± 0.888	8.200 ± 0.325	20.200 ± 0.949
	F value	1.926	0.55	1.444
	p-value	0.132	0.649	0.236
Farmers registration status	Not registered	14.895 ± 0.799	8.421 ± 0.288	19.789 ± 0.843
	Registered	16.079 ± 0.439	8.413 ± 0.288	21.238 ± 0.463
	F value	1.689	0.001	2.268
	p-value	0.197	0.98	0.136
Frequency of extension visits	Weekly	17.667 ± 1.945	8.667 ± 0.739	22.333 ± 2.016 ab
	Monthly	16.091 ± 0.718	8.409 ± 0.273	20.909 ± 0.744 ab
	Quarterly	17.111 ± 0.794	8.278 ± 0.302	21.222 ± 0.823 ab
	Semi-annually	15.867 ± 0.870	8.400 ± 0.331	22.333 ± 0.901 ab
	Annually	18.000 ± 2.383	8.000 ± 0.906	26.500 ± 2.469 a
	Never	13.955 ± 0.718	8.545 ± 0.273	18.955 ± 0.744 b
	F value	2.253	0.153	3.033
	p-value	0.057	0.979	0.015
Access to finance	No	15.125 ± 0.614	8.688 ± 0.218	20.188 ± 0.651
	Yes	16.240 ± 0.492	8.240 ± 0.175	21.360 ± 0.521
	F value	2.008	2.562	1.979
	p-value	0.16	0.113	0.163

Source: Table by authors. Note: * Values within a column, for the same socio-demographic category, that do not share a common letter are significantly different.

3.4. Farmers' Perception of the Intensity of Climatic Events Affecting Farms

The farmers' perception of the intensity of climatic events affecting their farms is displayed in Figure 4. The overall proportion perceiving an increasing trend was 60.7%. Specifically, the proportion of respondents who perceived increased

extreme dry seasons or droughts was 84.1%, those who perceived increased flooding was 68.3%. Those who perceived increased rainfall was 65.9%. In contrast, 28% of respondents perceived a decreasing trend in rainfall, and 22% perceived a decreasing trend in tropical cyclones. Among responses for no perceived change, 41.5% of respondents felt that the intensity of tropical cyclones had not changed. There were no statistically significant differences ($p > 0.05$) between mean perception scores and any of the socio-demographic categories assessed (Table 3).

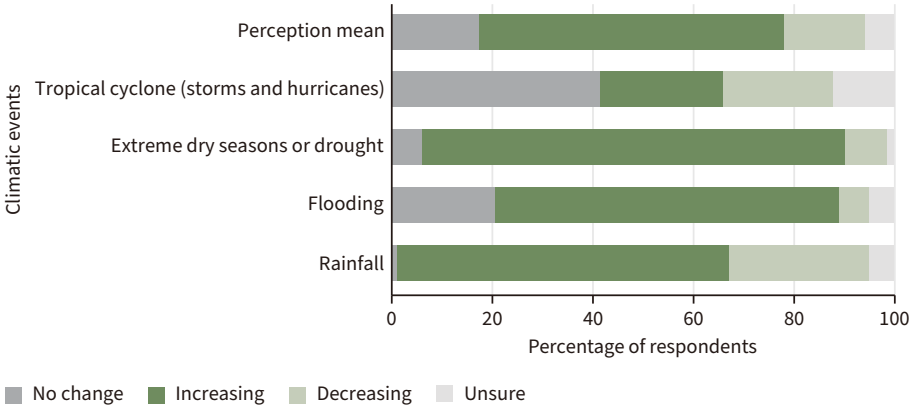


Figure 4. Farmers' perception of the intensity of climatic events affecting farms. Source: Figure by authors.

3.5. Farmers' Perception of the Severity of Impacts Associated with Climatic Change

Farmers' perception of the severity of impacts associated with climatic change is presented in Figure 5. Respondents acknowledged numerous impacts of climate change on root and tuber crop production, including reduced farming income, reduced marketable quality of produce, increased soil degradation, reduced annual cropping cycles, decreased yield quantity and quality, increased periods of crop stress, increased occurrence of pests and diseases, and increased water scarcity. The severity of these climate change impacts was perceived at different levels among respondents. Most respondents perceived the seriousness of all the impacts to be moderate to low. The majority of respondents perceived moderate impact for decreased yield quantity and quality (67.1%), increased periods of crop stress (62.2%), increased water scarcity (61%), and the increased occurrence of pests and diseases (52.4%). Water scarcity had the highest proportion of respondents with a perception of high impact (15.9%), followed by the increased occurrence of pests and diseases (11%) and reduced farming income (11%). Most respondents perceived that the

reduced marketable yield of produce had a low impact (53.7%). All respondents perceived that increased soil degradation due to climate change ranged from no impact to moderate impact but not high impact. This variable also had the highest proportion of respondents who felt it was of low impact (18.3%). As detailed in Table 3, statistically significant differences were detected for the perception of severity for the socio-demographic categories of household size ($p = 0.001$) and the frequency of extension visits ($p < 0.05$). It appears that farmers from households with less than 5 members had a significantly different and lower mean severity perception score (19.725 ± 0.479) compared to those from households with 5 to 10 members (22.893 ± 0.646). Furthermore, farmers that received extension visits annually had a significantly higher severity perception score (26.500 ± 2.469) compared to those who did not have any extension visits.

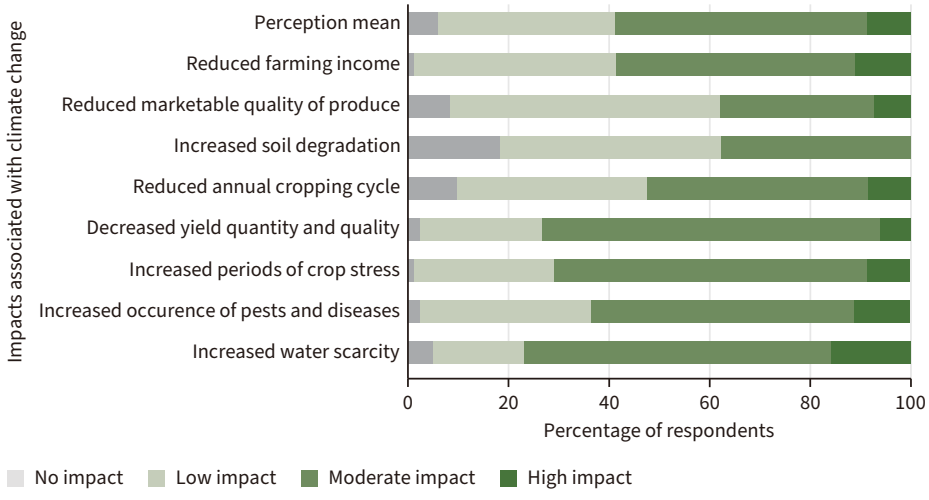


Figure 5. Farmers' perception of the severity of impacts associated with climate change. Source: Figure by authors.

3.6. Adoption of Coping and Adaptation Strategies Among Farmers

Climate change coping and adaptation strategies adopted by root and tuber crop farmers are shown in Figure 6. There were a range of adaptation strategies adopted which included reduced farm production, the increased use of agro-chemicals (biostimulants and biopesticides), diversifying farm income, switching to cultivars that are more tolerant to climatic conditions, improved soil conservation and management practices, switching to more efficient irrigation systems, and manipulating periods for cropping cycles. While all respondents

adopted at least one coping or adaptation strategy, none of these strategies were adopted by the majority of farmers. The coping or adaptation strategy with the highest level of adoption was 'switching to more efficient irrigation systems' (24%), followed by the 'increased use of biostimulants and biopesticides' (23.2%). The coping or adaptation strategy with the lowest level of adoption was 'switching to cultivars more tolerant to climatic conditions' (2.4%), followed by 'increased soil conservation and management practices' (4.9%) (Figure 6).

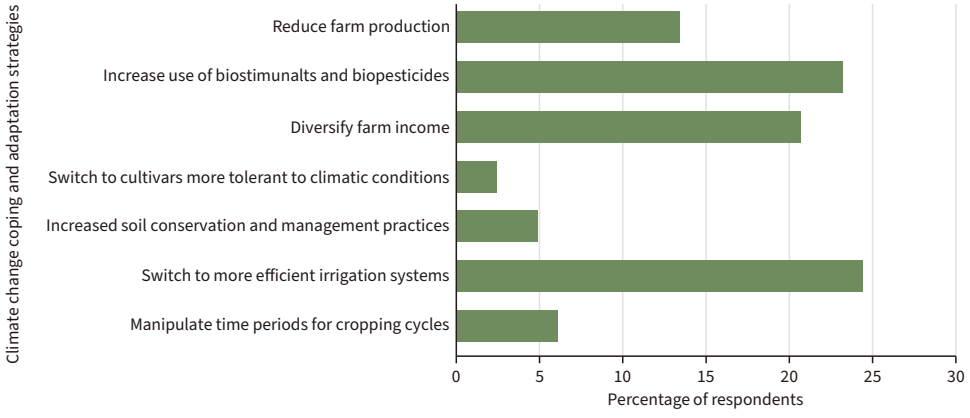


Figure 6. Climate change coping and adaptation strategies adopted by root and tuber crop farmers in Trinidad and Tobago. Source: Figure by authors.

4. Discussion

Climate change is increasingly recognized as a significant challenge to agricultural systems, especially crop production, worldwide (Arora 2019). Among the various crops vulnerable to its effects are root and tuber crops, which play a crucial role in global food and nutrition security. Understanding how farmers of root and tuber crops perceive climate change's impacts is essential for designing effective adaptation strategies to help farmers. This study therefore sought to investigate farmers' perceptions of climate change's impacts on root and tuber crop production. It explored potential implications for agricultural practices and policies in Trinidad and Tobago. The results of this study may also have applicability in other countries and regions to help improve root and tuber crop production globally. The findings of this study were generally consistent with other studies, which explored farmers' perception of climate change and its impacts in other tropical regions and countries and for different crops (Virgil and Pun 2023; Ashraf and Routray 2013; González and Velasco 2008). Nevertheless, there are some unique differences based on the

crops being explored and the location. This study also underscored the need for cross-disciplinarity and an integrated approach to assessing climatic trends and people's perception of those trends and their impacts (Shrestha et al. 2022; Hitayezu et al. 2017; Connolly-Boutin and Smit 2016; Roco et al. 2015). Perceptions of climate change may be influenced by several factors such as expectations and the time at which an event occurs. This makes predicting perception challenging. Additionally, farmers' perception may not necessarily reflect reality and as such it may impede their adaptive capacity in dealing with increasingly severe future climate change impacts (Budhathoki and Zander 2020). For example, Roco et al. (2015) posit that the recent occurrence of a climatic event may influence how severely or intensely a farmer may perceive that climatic event.

Most farmers perceived shifts in weather patterns and growing conditions, occurring in recent years, in terms of the frequency, intensity, and severity of climatic events. The survey indicated that a significant number of farmers are facing altered rainfall patterns, extreme dry seasons or droughts, and increased flooding, consistent with global trends that affect agricultural productivity (Pörtner et al. 2022; Kogo et al. 2021). For example, in Chile, González and Velasco (2008) reported that 97% of the farmers surveyed had perceived prolonged droughts, higher average temperatures, and alterations in the growing season for several crops. Additionally, Ashraf and Routray (2013) concluded that farmers' perceptions regarding climatic variability, temperature increases, and drought in north-west Balochistan, Pakistan, were in conformity with results obtained through analyzing climatic data over 36 years to as much as 113 years by various other researchers. Finally, in Trinidad and Tobago, a recent qualitative study examining the factors influencing climate change adaptation measures in farming communities reported that most farmers implemented strategies to adapt to extreme weather conditions, based on their awareness of periods of low rainfall and flooding (Virgil and Pun 2023). Farmers perceive and experience the impact of climate change in several ways. Among the farmers in this study, decreased quantity and quality of yields were among the most frequent impacts reported with a moderate and high impact. Several studies have also projected that climate change will cause a reduction in crop yields (Ray et al. 2019; Vogel et al. 2019). Farmers have observed a decline in both the quality and quantity of essential crops such as cassava and sweet potatoes, aligning with global reports on climate impacts (Pörtner et al. 2022). Furthermore, there have been reports of farmers already experiencing crop failure and reduced yield due to the prevailing climatic conditions in several regions of the world (Verschuur et al. 2021; Beillouin et al. 2020). Several factors are associated with reduced quantity and quality of produce, including water

scarcity, heat stress, and increased pest and disease pressure, which are exacerbated by changing climatic conditions. Many of these factors are intertwined and the results reported in this study show that farmers recognize the co-occurrence of these impacts. Socio-demographic factors highlighted in this study prove to be relevant to how climate change is perceived. Consistent with findings by Virgil and Pun (2023), the results of this study indicate that education level influences farmers' perception of climate change in Trinidad and Tobago. In this study, the significantly higher mean perception score among respondents whose highest education level was secondary school, compared to respondents with no formal education, is an indication that formal education may be an important tool in assisting individuals in their understanding of climatic events and their impacts on farming practices. When this is coupled with differences observed in the perception of climate change based on the exposure to extension visits, this further emphasizes the importance of ongoing education for farmers. More educated farmers feel more confident in interpreting the information they are exposed to and are also in a better position to act on that information. The current study agreed with other studies in several other regions which concluded that farmers' educational level was a significant determinant in their perception and ultimate adoption of climate change adaptation strategies (Belay et al. 2022; Marie et al. 2020; Dang et al. 2019; Trinh et al. 2018; Below et al. 2012). This study also revealed that household income and household size influence the perception of climate change and its impact. Interestingly, farmers in the medium categories for combined monthly household income (i.e., USD 2501–5000) had a higher perception mean compared to those in the lower income (i.e., USD < 1001) and higher income (i.e., USD > 10,000) categories. This shows that the relationship between income and perception of climate change is not straightforward and should be interpreted in combination with other factors and various vulnerabilities that may influence household income. Some of these factors that may impact farmers in this particular situation include non-climatic ones such as the level of land development and drainage, and rising cost of farming inputs, including fertilizers, pesticides, and machinery (Virgil and Pun 2023; Mahase 2022). Farmers from smaller households had lower mean perception scores of climate change and its impact. This may be indicative of those farmers having more disposable incomes which may contribute to less concern about climate change and its impacts. While both socio-demographic indicators of household income and household size suggest that financial factors are relevant in climate change perception, it should be noted that as much as 60% of the farmers did have access to finance and this variable did not influence the perception of climate change by farmers. This situation may suggest that farmers should view

the availability of financial resources or financial stability through multiple lenses, particularly in terms of their influence on climate perception. Furthermore, this study also suggests that finances are an influencing factor as early as the point at which climate change is perceived by farmers, and not only from the point at which farmers must consider adopting climate-resilient strategies. The early impact of financial considerations also corroborates the point by Virgil and Pun (2023) that local farmers require assistance in bolstering their resources so that they are better able to maintain or improve their livelihoods as they adjust to climate risks. This is also an important consideration for policy makers.

Farmers are employing adaptation strategies to mitigate the impacts of climate change on root and tuber crop production. Based on this study, these include adjusting to more efficient irrigation systems, the increased use of agro-chemicals, and diversifying cropping systems to enhance income and resilience. Similar types of interventions were reported by Virgil and Pun (2023). In turn, the adaptation strategies selected were adopted to buffer perceived water scarcity, crop stress, and reductions in the quantity and quality of yield, which were perceived as having a moderate level of impact by 60%–67% of the respondents. This demonstrates a level of alignment between what is perceived and what is adopted by farmers. These climatic changes present substantial challenges for growing staple crops critical to the dietary and economic well-being of Caribbean communities. In fact, despite their efforts to adapt, farmers often express concerns about the long-term viability of root and tuber crop production in the face of escalating climate change impacts. They highlight challenges such as limited access to resources, financial constraints, and insufficient support from government agencies or agricultural extension services. Despite this recognition, the adoption of adaptation strategies varied widely in this study, echoing findings from previous research (Barrett et al. 2024; Connolly-Boutin and Smit 2016; Allemann et al. 2004). For example, while close to 80% of the farmers perceived some type of climatic change, none of the seven (7) adaptation strategies were selected by more than 25% of the farmers, indicating that a gap exists. This suggests that the success of these strategies might depend on how well they are tailored to meet the diverse needs of the farming community. Furthermore, the effectiveness of adopting new practices such as enhanced irrigation systems and the cultivation of new crop varieties that are more climate-resilient depends heavily on the availability of adequate technical support and resources, which many farmers report as insufficient. Compounded by rising pest and disease incidences, these challenges demand prompt and effective adaptation strategies to maintain agricultural productivity and community resilience. This association highlights that

types of extension services are critical. There is a need for extension services tailored to the diverse backgrounds of farmers, thereby enhancing the dissemination of critical information on climate resilience and supporting climate action in agriculture.

5. Conclusions

This study investigated perception and adaptation behaviours and strategies among root and tuber crop farmers in Trinidad and Tobago. The findings highlight a critical intersection between climate change, agricultural productivity, and food security. Based on the results of farmers' perceptions of climate impacts on their crops, there is a heightened awareness, within the root and tuber crop farming community, with regard to shifts in climate. Nevertheless, translating this awareness into tangible, effective adaptation strategies is still in its nascent stages, marked by significant disparities in access to necessary resources, knowledge, and support services. This research therefore enriches the academic and practical understanding of the specific challenges and adaptations concerning root and tuber crop production in the Caribbean. It emphasizes the need for targeted policy interventions that are deeply informed by farmers' real experiences and challenges, tailored to strengthen their resilience and adaptive capacities in an increasingly unpredictable climate system. Moreover, this study advocates for the expansion of specialized extension services that cater to the varied needs of the farming community. These services should provide customized advice that helps farmers tackle the complexities of climate adaptation and their personal circumstances thereby enhancing their productivity and long-term sustainability in the agriculture sector.

6. Recommendations

Although there have been some advances in adopting new irrigation techniques and alternative fertilizers, a substantial gap remains in the broad application of more sophisticated, technology-driven solutions. This gap signals a broader necessity for policy reforms that focus on fortifying agricultural support systems, increasing access to climate-resilient technologies, and nurturing a culture of knowledge exchange and capacity building among farmers. There is a need for a support network that includes enhanced, readily accessible extension services tailored to the diverse demographics of the farming community. Such systems would not only improve farmers' capacity to deploy effective adaptation measures but also strengthen the sustainability and resilience of agricultural production amid intensifying climate challenges. Further studies should explore the efficacy of specific adaptation strategies, offering different perspectives on their influence on agricultural output and farmer livelihoods. By

addressing the identified knowledge gaps, this research holds the potential to significantly strengthen the resilience of root and tuber crop systems against climate impacts. This not only protects food security but also contributes to achieving the SDGs, particularly SDG 13—which demands urgent action to combat climate change and its effects. Continuing this research is crucial for developing resilient agricultural models that can be replicated globally, ensuring that root and tuber crop production can prosper despite the escalating challenges of global climate change.

7. Future Research Directions

Based on the insights gained from this study, several future research areas emerged. Firstly, there is a need to conduct longitudinal studies that monitor changes in farmers' perceptions and adaptation strategies to climate change over time. Such studies would improve our understanding of the dynamic nature of climate awareness and behavioural shifts in response to evolving climate conditions, farmers' technological adaptations, and policy interventions.

Secondly, expanding the geographic scope of the survey to focus on diverse agro-ecological zones in other countries and regions would provide comparative insights and deeper perspectives into how local environmental, cultural, and socio-economic contexts shape root and tuber crop farmers' climate responses. This can enhance the development of country and region-specific adaptation strategies that are both culturally appropriate and agro-ecologically relevant.

Thirdly, integrating participatory research methods, such as focus group discussions and farmer-led monitoring, could offer deeper qualitative insights into the decision-making processes behind root and tuber crop farmers' adaptation behaviours. These approaches can complement quantitative survey findings by capturing local knowledge and experiential learning that are often not captured in structured questionnaires.

The fourth critical area for future work involves linking climate perception and adaptation data with agricultural productivity and resilience metrics. This would allow for an assessment of the effectiveness of various adaptation strategies and their impact on household and national food security and income stability.

Finally, future studies should consider the role of institutional support, such as access to extension services, climate information systems, and financial mechanisms (e.g., crop insurance, microcredit) in shaping adaptation behaviours. Identifying gaps in institutional engagement can inform more targeted and inclusive policy interventions aimed at empowering root and tuber crop farmers as key agents in climate action within agriculture.

8. Limitations

This study is not without limitations, and it is important to understand these limitations to interpret the context of the study better. Firstly, this was a cross-sectional study, the outputs were descriptive, and inferences were limited by the study design, sample size, and statistical methods used. The use of online recruitment tools as one option used in this study had inherent limitations such as the need for participants to be literate and have internet access. Because of this, the use of online surveys may have excluded some groups or limited the number of respondents from some socio-demographic categories. The timing of the survey may have had an impact on farmers' views, and their views may have been different if they had a longer time to reflect on their responses. These likely impacted respondents' perceptions to the stated issues. Therefore, the findings presented should not be generalized but rather taken in the context of the farmers sampled, some of whom had access to the various online resources used to collect data, and their socio-demographic categories.

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Climate Change-Induced Gender-Based Violence (GBV) Against Men and Boys in the Caribbean

Roshnie A. Doon

1. Introduction

Climate change events such as variations in the weather conditions around the globe have been linked to an increase in gender-based violence (GBV) in several studies and reports, such as Agrawal et al. (2023), through multiple interconnected pathways. Extreme weather events such as flooding, heat waves, droughts, wildfires, tornadoes, tropical cyclones, and storms are known to exacerbate GBV because they heighten the risk that victims may encounter violence, exploitation, and human trafficking during disaster-induced crises (Soliman et al. 2022). Even though these events in themselves do not directly cause GBV, they can amplify and create an environment in which the underlying drivers of such violence can grow and thrive. This is mainly because during and after climate change events, victims may experience many issues such as gender discrimination and the persistent economic instability of their households, which influences their ability to access safe forms of housing, healthcare, and food supplies for their families (Van Daalen et al. 2022).

It is within the context of reduced access to resources to deal with the negative fallout of climate change events that there is a rise in the incidence of GBV events, which brings to the forefront concerns of (1) pre-existing gender disparities, such as structural inequalities within the household and the community regarding access to education, healthcare, and access to climate change relief, (2) the intensification of patriarchal pressures, which may lead to a rise in child marriages to reduce financial burdens, and finally (3) the worsening of armed conflict in politically and economically fragile countries like the Federal Republic of Somalia (Soliman et al. 2022). Given that the implications of these events for all individuals around the world, particularly in low- and middle-income countries, are not the same, as victims may suffer greater instances of GBV within their population segments than in more highly developed countries (Chancel et al. 2023).

The Sustainable Development Goals (SDGs) adopted by the United Nations (UN) in 2015 were a universal call to action that aimed at enhancing the peace and prosperity that people around the world can experience by addressing several

targets of its 17 goals of SDG 1—no poverty; SDG 2—zero hunger; SDG 3—good health and well-being; SDG 4—quality education; SDG 5—gender equality; SDG 6—clean water and sanitation; SDG 7—affordable and clean energy; SDG 8—decent work and economic growth; SDG 9—industry, innovation, and infrastructure; SDG 10—reduced inequalities; SDG 11—sustainable cities and communities; SDG 12—responsible consumption and production; SDG 13—climate action; SDG 14—life below water; SDG 15—life on land; SDG 16—peace, justice and strong institutions; and SDG 17—partnerships for all the goals.

Focusing on Goal 13, i.e., climate action, calls for urgent action to combat the often irreversible and direct consequences of climate change and its wide-reaching impacts by calling for an enhanced level of resilience and adaptive capacity through sustainable practices, transitioning to the use of renewable resources, and the mitigation of greenhouse gas emissions (UNDP n.d.). Through these efforts, countries around the world, particularly those vulnerable to climate change events, aim to create a more sustainable future for future generations while protecting the planet. Although SDG 13 (climate action) is crucial in itself to combat the global challenge that climate change presents to countries worldwide, this goal is deeply interconnected with the entire 2030 agenda for sustainable development, because changes in the climate can adversely impact the rate at which many of the other SDGs such as SDG1 (no poverty), SDG 2 (zero hunger), and SDG 6 (clean water) are achieved. This is mainly because many SDGs can be achieved by using adaptive responses to climate change through resource building and resilience, promoting sustainable practices across cities and economic sectors, and altering domestic energy systems to reduce poverty and food insecurity (UNDP n.d.). Thus, failure to act on climate change can unavoidably undermine progress already made on these goals.

Concentrating upon the link between climate action (SDG 13) and gender equality (SDG 5), while the targets of both goals may appear different on the surface, they have several key areas of importance and interest, because when natural disasters occur they often bring about further calamities to vulnerable populations such as women and girls around the world. As discussed by Filho et al. (2023), adverse climate change events, such as droughts, heatwaves, hurricanes, and extreme rainfall, tend to impact poorer and marginalized community members due to pre-existing gender inequalities, including limited access to resources and social protection. The reduced social protection, according to SI (2025), can exacerbate violence against women and girls (where by the end of 2100, 1 in 10 cases of Intimate Partner Violence (IPV) will be linked to climate change, and by 2090 with every 1 °C increase in temperature there will likely be a 4.7% increase in IPV) and reduce

their participation in the global dialogue on environmental human rights, while their economic instability may disrupt social ties due to the heightened frequency of abuse and violence.

Bearing in mind the strong linkages that climate change has with GBV, there is a need to incorporate inclusive policies that support these marginalized communities to build their resilience and adaptive capacity towards climate-related disasters such as GBV (Soliman et al. 2022). The discussion on the link between climate change and the prevalence of GBV, however, has traditionally focused on how these events have impacted women and girls in vulnerable countries worldwide because they disrupt their ability to provide food, housing, and security for their families. The inability of women to undertake their household tasks is, when disrupted by climate change events, often what makes them more vulnerable to experiencing GBV, as there may be disagreements over how limited household funds and disaster relief funds may be used (Roett et al. 2022). While men and boys are perceived as the perpetrators of GBV, there is little focus on how they are impacted by climate change events and the part that these events play in the prevalence of GBV against men and boys around the world (Rao et al. 2019).

A more in-depth examination of the literature on GBV against men and boys reveals, however, that not only do men and boys experience the impact of climate change differently to women and girls, but vulnerable male victims, i.e., youths, the elderly, the disabled, and those from low-income countries and households worldwide who dwell in destitute conditions, may be adversely affected by climate change events (Ahmed and Eklund 2021). These groups of men and boys may become victims of GBV because, like vulnerable women and girls, they too are responsible for taking care of their families during and after the occurrence of natural disasters (Nelson et al. 2002). As a result, they too lack support and experience feelings of powerlessness brought on by the inequitable access to resources, which may leave them exposed to acts of GBV (Allen et al. 2021).

Within the literature on the gendered aspects of climate change, there has been much discourse on its relationship with GBV amongst women and girls; however, there is limited awareness of the intersection of male experiences in the Caribbean. Such an outcome in the Caribbean may be due to factors such as (1) a lack of data and expertise on GBV against men and boys, (2) a greater emphasis on women and girls during policy development because of gender roles and power imbalances, (3) a lack of research on gender issues related to male victims, (4) limited awareness and implementation of gender policy, and (5) societal stigma and discrimination that

limit open discussion of male victimization in the context of GBV (UN Women and IISD 2021).

Considering the limited knowledge in the literature, this chapter will seek to fill this research gap by using a conceptual research methodology to examine climate change-induced GBV against men and boys in the Caribbean. In doing so, this chapter from the perspective of the Caribbean concerning climate change will examine (1) the literature on GBV against men and boys, (2) the presence of male GVB in the Caribbean and the impact that climate change events have on men and boys, (3) the role that climate change plays in worsening the prevalence of GBV against men and boys, and finally (4) the barriers and solutions to GBV against men and boys during climate change events.

2. Research Methodology

To explore the presence of climate-change-induced GBV against men and boys in the Caribbean, a conceptual research methodology was used. This methodology used the existing scholarly literature to develop theoretical ideas, as well as interpret and analyze existing concepts to generate new frameworks in a new context, while complementing empirical research by providing a solid theoretical background. The conceptual research methodology was considered appropriate for this study because it allowed for a rounded discussion on the complex dynamics associated with the drivers of GBV against men and boys presented by various stakeholders, which may have occurred during climate change events not only in the Caribbean but also in other countries around the world that are especially vulnerable to natural disasters such as hurricanes, wildfires, and extreme flooding events (Mtotywa et al. 2023).

By incorporating the acumen of various stakeholders such as governments, international organizations (United Nations, World Bank, and European Commission), civil society organizations (inclusive of non-governmental agencies, community-based organizations/leaders, and advocacy groups), the private sector, research and academic institutions, faith-based organizations, and media, this method took a multifaceted approach to capturing the various socio-economic, cultural, and individual factors that may have influenced the presence of GBV against men and boys during/after climate change events in the Caribbean (Mtotywa et al. 2023). In doing so, such a methodology not only situated GBV against men and boys within gender theory and supported the design of solutions/response strategies that are tailored to the conditions prevailing during/after climate change events, but also addressed methodological challenges such as the lack of comprehensive data collection on GBV in the Caribbean region (Maina et al. 2024).

Further to this, the lack of GBV data may limit empirical research studies, because there may be a greater focus on reporting incidents rather than addressing the root causes of GBV, inconsistent data collection mechanisms, concerns about data protection and ethics, slow development of gender statistics systems, and limited resources and human capacity to collect systemic GBV data in the Caribbean (PARIS21 and UN Women 2024). The use of the conceptual framework for this study is then crucial to first the identification of information gaps, and second the collection of data on GBV against men and boys during climate change events in the Caribbean, as the framework of the discussion may guide the collection and analysis of data to facilitate the quantitative analysis of the themes highlighted in this study.

In the case of this study, as reflected by Figure 1, the literature was used to examine (1) the intersection between climate change and GBV against men and boys in the Caribbean and (2) the barriers and solutions to addressing such violence during climate change events in the Caribbean. Following a review of the literature on GBV against men and boys in the Caribbean, the two frameworks and the critical themes under each were then developed and examined. The first framework examined the impact that climate change events have on men and boys in the Caribbean by looking specifically at their migration and risk-taking behaviors, patterns of conforming to climate change policies, and manifestations of healthcare outcomes and inequality.

The second framework sought to analyze the role that climate change plays in exacerbating GBV against men and boys in the Caribbean by assessing how it not only leads to economic and psychological instability but also creates a cyclical process of crisis through the breakdown in the victims' social support network. The third and final framework focused on highlighting the barriers that male victims of GBV may experience during climate change events, and the viable solutions/strategies that can be used to address problems that arise under the specific themes of societal stigma, cultural norms, perception, security, and legislation.

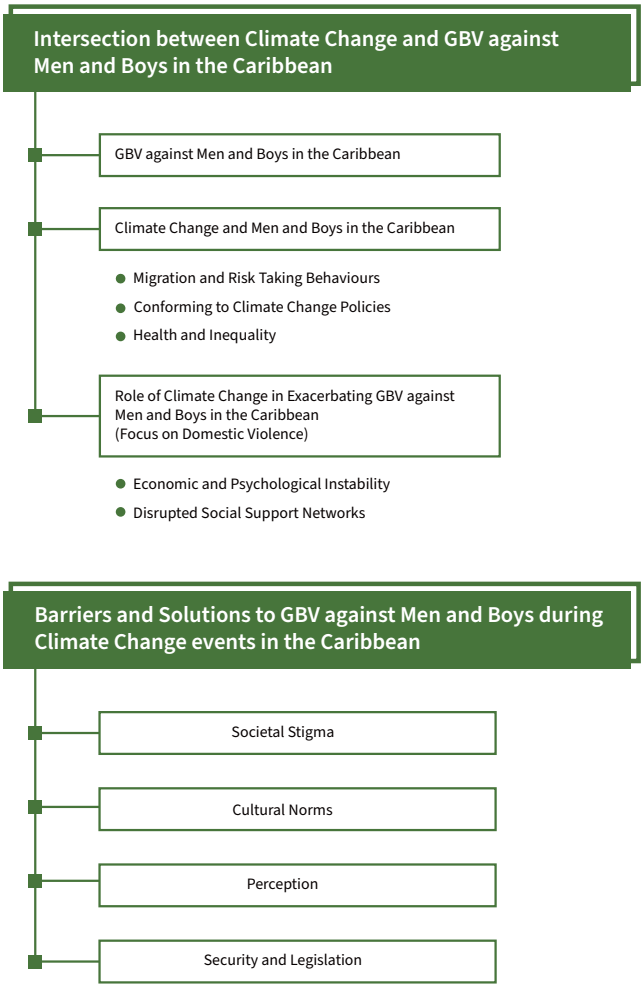


Figure 1. Literature map of the intersection between climate change and GBV against men and boys in the Caribbean. Source: Figure by author.

3. Perspectives on Male Gender-Based Violence (GBV): A Brief Review of the Literature

GBV against men and boys refers to any violence that can be perpetrated against men and boys and can take the form of physical violence, e.g., hitting, slapping, and kicking, and emotional violence, such as insults and humiliation (Auchter 2017). Although the literature on GBV tends to focus a great deal on women and girls as

the primary victims of domestic violence, and men and boys as the perpetrators, the latter group can also become victims of such violence (Akhter and Kusakabe 2014).

Although largely ignored in the literature, within the literature on GBV against men and boys there are several examples of such violence, which has been exhibited in situations of armed conflict such as those in the Democratic Republic of Congo (DRC) and South Sudan, where acts of violence were used as a form of terrorism against male refugees to not only generate feelings of emasculation but to create an environment of fear and intimidation (Ngari 2016). In the context of conflict-related situations, there have been several situations in countries such as Palestine and Somalia where the abuse of male victims has been perpetuated by persons from other tribes, armed groups, and community members, and it has been found to occur quite frequently in other cities in Kenya such as Nairobi and Mombasa (Mongare et al. 2018). As a consequence of such violent acts, Touquet et al. (2020) and Chynoweth et al. (2022) identify that such vulnerable men in other countries like Libya, the Syrian Arab Republic, the Republic of Sudan, and the DRC can not only experience mental health issues, but also encounter such abuse within the prison system, nursing homes, while crossing borders, at checkpoints, point of capture, refugee camps, and even during village attacks.

Under such unstable economic situations, institutions and organizations are often reluctant to engage with the issue of GBV against men and boys because of fears of being labeled as prejudiced against women, as it shifts the attention from the experiences of females to males (Taylor et al. 2021). This has been demonstrated by the lack of laws and legislation to protect male victims in countries like the DRC, Central African Republic (CAR), Myanmar, Nigeria, Sudan, Syria, and Yemen (Dolan 2014). As a direct consequence of this, men and boys are more likely to continue to be victims of such abuse because they receive little support, as the issue of GBV amongst male victims continues to remain a hidden issue, which perpetuates the underreporting of such violence.

Even though GBV is a human rights violation that affects all genders, it is underreported because of the cultural expectations of men and boys. They are often portrayed as being the stronger, i.e., more masculine, of the two sexes; however, the dominant way in which they are viewed can also make them vulnerable (Buiten and Naidoo 2020). The reporting of such abuse from such a cultural perspective not only deprives the man of his role in his household and community but may also diminish his identity (Touquet et al. 2020). Even with the presence of abuse, such emasculation can be made worse as he may experience feelings of shame, guilt, stigmatization, ostracization, ridicule, isolation, and homophobic backlash within his home and

community (Chynoweth et al. 2022). For this reason, male refugees who reside in countries like Western Uganda are unwilling to disclose the crimes committed against them, as this can also compromise their marital prospects (Ngari 2016).

The underreporting of such acts is also perpetuated by the inability of persons working with male victims to identify the indicators of male gender-based violence, such as unexplained changes in sleeping patterns and appetite, avoiding people or places that remind the victim of the assault, feelings of emasculation, shame, and guilt, withdrawal from family members, and increased isolation (Ngari 2016). Such a lack of training among aid workers, crime investigators, and law enforcement agencies to both recognize and deal with male abuse often leads to reports and testimonies of male violence being inaccurately recorded as acts of terrorism or torture, rather than abuse and violence (UNHCR 2012). Furthermore, such underreporting may have resulted in not only less data being collected, but also less empirical research being performed to highlight cases of GBV against men and boys, as well as policies and strategies being developed to deal with the instances of such violence and abuse.

The unfortunate outcome of the impact of GBV on male victims is that it not only leads to negative health consequences, such as mental illness, suicide, and physical injuries, but may also cause men and boys to develop socially destructive tendencies such as substance abuse, e.g., drug and alcohol, violent behaviors, and deviant behaviors at the workplaces of victims (Bodankin and Tziner 2009). In cases where destructive deviance in the workplace is detected, this tends to create a ripple effect as (1) victims may experience a decline in their mental health, which may spill over into their household dynamics, (2) it may create resentment among employees and normalize the occurrence of aggression within the workplace and erode organizational trust, and (3) reinforce the presence of systemic inequality within communities through the continued marginalization of men from minorities and vulnerable groups, as well as the validation of unethical behaviors (Nadeem et al. 2020).

4. The Intersection Between Climate Change and GBV Against Men and Boys in the Caribbean

4.1. GBV Against Men and Boys in the Caribbean

Male gender-based violence (GBV) in the Caribbean is a complex and often overlooked issue within the broader context of GBV, which primarily affects women, because historically most GBV cases have involved violence towards women of various forms, such as physical, emotional, verbal, and financial abuse. It is important to note, however, that men and boys can become victims of GBV from partners,

family, or community members, even though they have historically been portrayed as the perpetrators in domestic violence cases in Caribbean countries like Trinidad and Tobago, where they comprise nearly 87% of the perpetrators (UNTT 2025). Notwithstanding this, in the Caribbean, like many different regions around the world, there is a significant amount of underreporting of violence against men and boys and lack of collection of reliable data on male victims, because the societal expectations and the sociocultural norms that dictate many Caribbean households often discourage and stigmatize the reporting of such abuse, which leads to men and boys becoming victims of domestic and economic violence, as well as emotional and psychological abuse.

Even though there is a dearth of empirical research studies that focus on GBV against men in the Caribbean, this reflects the absence of a comprehensive dataset for male victims in the region. Still, in some instances, there are a few studies, such as Boduszek et al. (2017), Le Franc et al. (2008), Myrttinen (2023), and others, that have highlighted the prevalence of this pressing issue in the Caribbean. Joseph and Jones (2023) found in the case of the Caribbean, Boduszek et al. (2017) in the case of Barbados and Grenada, and Van Wijk (2012) in the case of victims in the Caribbean island of Curaçao that the concept of domestic violence and male victimization amongst men and boys in these regions was often influenced by not only the victims' (1) exposure to several different types of violence, such as within the home, community, and school environment, as well as by mass media and by being the primary (target of physical violence) or secondary (observer of violence) victim, but also (2) systemic gender inequalities.

The widespread patterns of discrimination and the marginalization of male victims of domestic violence in the Caribbean have unfortunately led to the depreciation or denigration of violence against male victims and females as perpetrators of such violence (Boduszek et al. 2017). The existence of such inequality plays an important role in the prevalence of GBV against men in the Caribbean as it (1) may make it difficult for male victims to access resources when seeking support, thus leading to feelings of isolation as well as the silent acceptance/tolerance of such violence and (2) may lead to the transmission of intergenerational trauma in Caribbean households amongst future generations (UNFPA 2025). This is especially important, as while reports of GBV against men in the Caribbean have remained historically low, Le Franc et al. (2008) found that 59% of male victims from Barbados, Jamaica, and Trinidad and Tobago stated they have experienced mainly physical violence/abuse, as well as emotional and verbal abuse perpetrated by their female partner within adversarial relationships.

At the country level, male victims in Barbados appear to experience the most physical violence (44.7% in Barbados, 40.4% in Jamaica, and 47.7% in Trinidad and Tobago) and sexual coercion (39.6% in Barbados, 57.2% in Jamaica, and 52.2% in Trinidad and Tobago) when in relationships, with an overall encounter of any type of violence of 63.1% in Barbados, 72.5% in Jamaica, and 71.2% in Trinidad and Tobago (Le Franc et al. 2008). When considering the presence of Intimate Partner Violence (IPV), Le Franc et al. (2008) found that the proportion of male victims who suffered from psychological aggression was higher in Barbados (76.1%) and Trinidad and Tobago (66.6%) than in Jamaica (66.5%), and a similar outcome was observed for male victims of physical violence; i.e., Barbados (44.7%) and Trinidad and Tobago (47.7%) were higher than Jamaica (40.4%). However, the levels of sexual coercion were notably higher in Jamaica (5702%) and Trinidad and Tobago (52.5%) than in Barbados (39.6%) during 2003–2004.

Moreover, in the case of Curacao, 25% of men have experienced some form of domestic violence, while 39% of men have become lifetime victims, which was instigated by parents, family members, and friends (Van Wijk 2012). Additionally, Boduszek et al. (2017) noted that boys in both Grenada and Barbados often observed non-interpersonal violence in the household, i.e., traumas that do not involve interaction with another person, and became the victim of physical violence and sexual abuse both inside and outside of the household. These types of traumatic events are caused by other types of distressing events such as exposure to natural disasters (earthquakes, extreme flooding events, hurricanes, wildfires, and droughts), car accidents, diseases, such as during the COVID-19 pandemic, and environmental pollution.

Building on the previous point, in Jamaica and Trinidad and Tobago, young, incarcerated men were found to be more likely to have been exposed to instances of domestic violence if, during their formative years, they grew up in a household without parents/guardians (Myrttinen 2023). However, in the case of male victims in Trinidad and Tobago and Jamaica who are not incarcerated, the prevalence of domestic violence was strongly connected to societal expectations of masculinity, male dominance, gendered performance, and the normalization of violence in the Caribbean (Myrttinen 2023).

Similar findings were made by Joseph-Edwards and Wallace (2021), who found that cases of male victims of domestic violence and intimate terrorism violence in Trinidad and Tobago, which were perpetrated by their female partners, were often leaked by third parties such as social media, documents, and information shared by employees or colleagues, without the consent of the victim. As feelings

of emasculation and worthlessness set in, even when male victims of domestic violence in Trinidad and Tobago attempt to work together and reduce tension with their partner to address problems in the household, they may attempt to mask their emotional pain by not only turning to substance abuse and gambling but also not engaging with their abusive partner by staying out or returning home late, listening to music/sleeping in their cars, praying, and engaging in physical exercise (Joseph-Edwards and Wallace 2021; Wallace 2025).

Other findings were made in an earlier study by Wiltshire (2012), which also found that the concept of masculinity and the acceptance of violence were key factors in the prevalence of GBV across countries in the Caribbean, like Trinidad and Tobago, Jamaica, Guyana, Suriname, and Belize. As a result, in countries like Trinidad and Tobago, where 20% of domestic violence victims are men, reports are not only not being made, but those that are made are also not being completed (Lindo 2022). This is simply because male victims may not want to appear weak to their social group/peers, may want to preserve their family dynamics, particularly where children are present, to provide an illusion that they are still in control of the situation, and finally may want to reduce the view of being less manly by their social groups and persons in authority (Jones et al. 2017; Cummings 2022).

In addition, regarding the experiences of male domestic violence victims in the case of Trinidad and Tobago when it comes to the lack of disclosing their status within their social group, it came down simply to the fear and embarrassment they felt when speaking to either security, health, or social support staff, i.e., persons outside of their social network, about female-perpetrated victimization (Joseph-Edwards and Wallace 2021). However, in Trinidad and Tobago, it was found that it was often a senior male figure within the household, such as a father, and either colleagues or customs within the working environment that encouraged victims of male domestic violence to seek help and support, as the offences experience are widespread, from sexual offences, assault and battery, psychological abuse, and verbal abuse to threats (Joseph-Edwards and Wallace 2021; Thomas 2021).

4.2. Climate Change and Men and Boys in the Caribbean

Within the literature that examines the impact of climate change events around the world and in the Caribbean, there is great emphasis on their negative implications that influence the lives and livelihoods of women and girls, rather than men and boys (Filho et al. 2023). However, men/boys and women/girls in the Caribbean tend to experience and perceive the impact of climate change events differently, because of variations in their social roles and responsibilities, attitudes towards risk

and sensitivity to vulnerability, knowledge of the economic cost associated with mitigation and adaptation strategies, cultural norms and values, and the presence of gendered policies that influences how different aspects of climate change advocacy are supported (Fruttero et al. 2023). For purposes of this section, emphasis will be placed on the experiences of male victims regarding migration and risk-taking behaviors, conforming to climate change policies, and, finally, health and inequality during/after climate change events in the Caribbean.

4.2.1. Migration and Risk-Taking Behaviors

Apart from the experiences of women regarding climate change events, there is a shortfall in the literature regarding the vulnerability of men and boys to climate change impacts, with subsequent marginalization of men and the injustices that they may endure in different communities, such as those living in coastal communities in the Caribbean (Ahmed and Eklund 2021). As mentioned earlier, these impacts are, however, shaped by many factors, in addition to occupational hazards and societal expectations of men, as they dominate high-risk professions linked to climate change events such as disaster response professionals, which often exposes them to physical and mental harm, as well as financial instability (Nagel and Lies 2022). Furthermore, Fruttero et al. (2023) explain that due to the risk-taking behaviors of men and boys, which are related to masculine norms and their physiology, they may exhibit a higher mortality rate during dangerous evacuation and recovery efforts.

In countries like Bangladesh, such risk-taking behaviors have been exhibited by men from coastal communities, who often come together with their families to migrate to inland cities to brace against the effects of tropical cyclones when they make landfall (Ahmed and Eklund 2021). A similar trend in movement is also observed amongst men from low-income households in Nigeria and the Mapai-Ngale community in Mozambique, who all migrate from their rural villages to urban communities and cities in response to periods of droughts to find jobs, while the women stay behind to care for dependent family members and to maintain farmlands (Akinbami 2021). Through such movement, men often enter new vocations rather than continuing either crop farming or animal husbandry.

Bearing in mind the experiences of these countries, it is possible with the rising incidence of extreme rainfall across the Caribbean, during the passage of hurricanes and tropical storms, that men and boys living in coastal fishing communities may migrate inland to urban communities to seek a better form of income and shelter, which may encourage greater risk-taking behaviors and a higher incidence of male mortality rates (Diakakis et al. 2015). The subsequent loss of men who are often

the main breadwinners of many Caribbean households, either through death or migration for better forms of work, can unfortunately destabilize households and communities, as climate change stressors often enhance the pressure on men/boys (UN Women 2024). The migration of men and boys during climate change events in the Caribbean can then increase their vulnerability, as they are moving to an unfamiliar environment where they may not have an established support network, legal protections, and financial resources (Henriksen et al. 2024). As a result, during their migration, as well as at their destination, male victims in the Caribbean increase their exposure to exploitative environments.

4.2.2. Conforming to Climate Change Policies

Men and boys often conform to climate change policies in different ways to women and girls, based on their perception of climate change policies. Nagel and Lies (2022) explain that climate science and policy have traditionally been influenced by masculine interests and perspectives. This influence stems not only from men's ability to modify their consumption patterns and access greater resources but also from their capacity to garner political support for issues such as climate justice. However, the degree of compliance with climate initiatives often hinges on the economic realities faced by men in both developed and developing countries. Even though men and boys in developed countries may be better able to adopt eco-friendly behaviors, support gender-responsive climate policies, and promote the use of sustainable technologies that reduce the susceptibility of both genders to the adverse effects of climate change, the same cannot be said for vulnerable men and boys from developing countries (UN Women 2016).

Vulnerable men and boys from developing countries and regions like the Caribbean, while being able to participate in community-based adaptation initiatives and agricultural practices, during times of climate crisis, such as droughts and the passage of hurricanes, may be more prone to experiencing negative outcomes (WHO 2014). The added burden of managing additional tasks related to crop care, livestock management, and selling produce, combined with a weak support system, may make male victims in the Caribbean more vulnerable to the impacts of poverty and hardship. This vulnerability can lead to health issues, including increased alcohol consumption and drug abuse, as well as a breakdown in family relationships, as substance abuse may serve as a coping mechanism (Whittenbury 2013).

Despite the hardship experienced, the negative outcomes of climate change can also become an opportunity for developing countries in the Caribbean region to create and strengthen the support networks of men to mitigate these vulnerabilities and

better conform to climate change policy. For example, in the provinces of Limpopo and KwaZulu-Natal in South Africa, men who lost their jobs to environmental changes have used this as an opportunity to come together to discuss not only these changes but also how to create a more supportive and caring community to ensure that vulnerable men and boys do not become victims of GBV (Goldin et al. 2017). A keen sense of community and mutual responsibility among members is essential for reducing the risk of gender-based violence (GBV) against men and boys during climate change events in the Caribbean. Those with higher incomes, more assets, better education, and access to information are better positioned to mitigate the impact of climate change on men and boys from low-income households and communities. This can help reduce their exploitation through several practical strategies, including the following: (1) advocating for a more equitable distribution of resources, (2) ensuring that climate action does not disproportionately burden certain groups, and (3) investing in community-led projects that create jobs to help these individuals adapt and thrive amid climate change events in the Caribbean (Anugwa et al. 2023; Emmerling et al. 2024).

4.2.3. Health and Inequality

Climate change events can also encourage the growth of inequality, not only between genders but also between different income groups and classes. In cases where men and boys from low-income households in coastal communities in the Caribbean are unable to either migrate, access support from their community, or communicate freely about their problems, they can not only be exploited by other community members but also experience a decline in their health, as reflected by the occurrence of chronic and mental health issues (Chynoweth et al. 2022). The potential for the mental and physical health of men and boys to worsen during climate change disasters often increases because they are more unlikely to seek either counseling or medical support because of societal expectations, the lack of accessible resources targeted at men and boys, and their age and overall health (Parkinson and Zara 2016).

According to Goh (2012), the age and overall health of men and boys are some of the barriers that prevent them from effectively adapting to the adverse effects of climate change events. That is, during periods of droughts in the case of Ghana and Nigeria, or even extreme flooding events in the Caribbean and Bangladesh, it is often able-bodied men and boys who can migrate and engage in recovery efforts. More vulnerable groups of men and boys who have reduced healthcare outcomes, because of restricted opportunities and resources, may not be able to do the same,

as their health erodes as a result of physical, psychological, and socio-economic factors (Rahman et al. 2025). This is especially important as, following the occurrence of a natural disaster, there can be a growth in the spread of insect-borne diseases like malaria and dengue fever and water-borne diseases like cholera, which can also be contracted by these vulnerable groups of men and boys in the Caribbean (Basiru et al. 2022).

Apart from natural disasters, changes in global weather patterns as exhibited through extreme temperatures have also been observed by Masika (2002) to impact men and boys in countries such as Ghana, Kenya and Mali, where they have become more vulnerable to extreme temperature and rainfall events than women. This is mainly because they hinder their ability to migrate, which is one of the most crucial climate change adaptation strategies adopted by adult men who are dependent on livestock and forestry for their source of income (Djoudi and Brockhaus 2011). Furthermore, extreme weather conditions such as periods of extreme flooding, droughts, and bushfires pose a significant threat to the food security and nutrition of men and boys in the Caribbean, who are at an increased risk of becoming undernourished and susceptible to infections and diseases (heat-related illnesses, respiratory and cardiovascular issues, and vector- and water-borne diseases) and developing mental health conditions such as anxiety, depression, and post-traumatic stress disorders, which can increase the risk of suicide and interpersonal violence (Goh 2012).

With such an erosion in the healthcare outcomes of men and boys, these climate change events are expected to have far-reaching implications for the Caribbean, as they not only disrupt the production of agriculture through reduced crop yields, but may also lead to (1) higher food prices, which makes food less affordable for vulnerable groups, (2) changes in the nutritional value of crops, (3) water scarcity, (4) displacement that is connected to a lack of job opportunities and risks of losing land assets, and finally (5) worsening of long-term health outcomes (Rao et al. 2019; Pratiwi et al. 2017). The vulnerability of men and boys to such health-related climate change risks can be worsened if they experience feelings of discrimination and marginalization, which can further erode their physical and mental health.

5. Climate Change and Its Role in Exacerbating GBV Against Men and Boys in the Caribbean: Focus on Domestic Violence

Although men and boys in general tend to manage and make significantly more headway before, during, and after climate change events than women, those who are more vulnerable may not be able to do the same. Given that such vulnerable groups

in the Caribbean are also responsible for taking care of their families during and after climate change disasters, they are more prone to becoming victims of GBV acts such as domestic violence within the home and community environment because of a combination of stressors that may disrupt the stability of the household and traditional gendered roles (Nelson et al. 2002). These key stressors according to Malivel et al. (2024) can include economic instability resulting from job loss and reduced household income during/after climate events, psychological instability resulting from a perceived loss of control, disrupted social support networks, and the undermining of gender norms and patriarchal structures, resulting in feelings of inadequacy amongst male victims, which can escalate into domestic violence. For the purposes of this chapter, focus will be placed on examining the areas of economic and psychological instability, as well as disrupted social networks.

5.1. Economic and Psychological Instability

Similarly to most households around the world, men in the Caribbean are also considered to be the breadwinners of most homes because of cultural norms, historical norms, and access to economic resources that enable their income to support an entire family, while the women play the role of the homemaker (Horrell and Humphries 2009). However, during climate change events like extreme flooding, food and income security becomes a major issue as vulnerable men and boys may not be able to secure gainful employment due to heightened job losses across sectors such as agriculture, fishing, forestry, tourism, and construction, which involve manual labor (Parent-Thirion et al. 2024).

As a result, vulnerable men, particularly those living in rural and remote communities in the Caribbean, are more likely to have less job security and protection and experience significant losses in terms of productivity. Under such conditions, Agrawal et al. (2023) argue that men may become more prone to experiencing psychological distress and a heightened sense of anxiety, as the dynamics of the household have now become disrupted and unstable financially. This may lead some women to not only express their dissatisfaction with their male partner's inability to provide for their families but also become either emotionally or verbally abusive.

The human cost associated with such instances of domestic violence when directed towards men and boys in the Caribbean may, unfortunately, worsen during climate change events because such job losses create financial stress and uncertainty, which can lower the threshold for disagreements to take place within the household (Bhalotra 2020). This raises the probability of friction taking place, as they may consume more psychoactive substances to cope with their feelings of inadequacy,

failure, frustration, and loss of identity (Bhalotra et al. 2021). This, in turn, may also lead to a downward spiral of violence within the home, as children may now be exposed to experiencing child abuse, and women, although being the initial cause of abuse towards their male partner by provoking them, may now experience "male backlash," through physical or verbal abuse (Allen et al. 2021).

In addition to this, male victims of domestic violence in the Caribbean may also be prone to experiencing negative psychosocial effects of climate change events, such as increased stress, anxiety, and post-traumatic stress disorders (PTSDs) due to the occurrence of natural disasters such as extreme heat and climate shocks, which may impair their judgement and increase both their irritability and aggression, leading to greater instances of violence (Woods and Agoncillo 2024). Such instances of long-term psychological impacts of climate change have been observed, including the 2009 Australian Bush fires, where Enarson et al. (2018) found that men and boys were more likely to feel the fallout from such natural disasters, such as anxiety, depression, adjustment disorders, suicidal thoughts, chronic stress from repeated disasters, and PTSD, even 5 years after they occurred. These deep-rooted effects can become protracted and lengthy for men and boys because of structural and attitudinal factors such as limited access to resources that are specially designed to treat male mental health, stigma and shame, preference for self-management, and dominant male ideals that make them less likely to seek help (Enarson 2006).

5.2. Disrupted Social Support Networks

Disrupted social support networks during climate change events, such as natural disasters and displacement, can increase men's risks of experiencing domestic violence in the Caribbean for a number of reasons. Firstly, due to heightened levels of economic instability and unemployment, vulnerable men and boys who are victims of domestic violence in the Caribbean may be less involved in climate change adaptation and mitigation strategies adopted by their communities (Malivel et al. 2024). As a result, such men and boys may not only have less access to resources such as food, shelter, and emergency aid, as well as vital information about climate change policies and strategies, but are more likely to have more intense feelings of isolation and stress due to the lack of social support (Alston 2013). In cases where men and boys in the Caribbean have weak support systems, they may be slower to adapt and recover from climate change events, which increases their risk of domestic violence as they lack a social support network that acts as a buffer against the stress that accompanies these events (ILO 2024).

The presence of a fragmented social support network then makes male victims in the Caribbean marginalized within their communities, as during periods of the climate crisis, there may also be greater discrimination and inequality against male victims of domestic violence, which can lead to higher levels of male suicides and homicides (Chandra et al. 2017). This may, unfortunately, worsen the level of inequality between men/boys within agricultural/farming communities, as landless men who rent land from large landholders may be heavily dependent on them for the land resources needed for the cultivation of crops even during extreme flooding events.

6. Barriers and Solutions to Addressing GBV Against Men and Boys During Climate Change Events in the Caribbean

According to Taylor et al. (2021), male victims of several types of GBV, such as IPV, around the world in countries such as Europe, Canada, Australia, the US, and the UK are less receptive to seeking support than women. Based on the literature, these barriers are heavily rooted in the sociocultural upbringing of men within their homes and communities around the world. These barriers, regardless of geographic location, are universal because they tend to originate from deeply rooted sociocultural and patriarchal norms, as well as the widespread perception that GBV affects women. As a result of this, the research on male victims has traditionally been overlooked, which creates a significant gap in the understanding of their experiences, as the awareness of such abuse remains limited. This lack of attention can perpetuate stereotypes and hinder support services tailored to men, contributing to an environment where male victims may feel isolated and unsupported in seeking help. Thus, for purposes of this chapter, emphasis will be placed on briefly discussing four of the main barriers to reporting and solutions to address them during climate change events in the Caribbean.

6.1. Societal Stigma

According to Arnocky and Vaillancourt (2013), there is limited knowledge of the challenges experienced by male victims of GBV because men and boys are often stigmatized, emasculated, and mistreated for making their concerns known, leading to feelings of minimization. These factors can create significant barriers for male victims who are seeking support and resources, as this may not only lead to a more pessimistic attitude towards men but further complicate their recovery. One of the reasons why this occurs is because male victimization within domestic violence situations has become so distasteful and strongly associated with the fear of not

being believed, stigma, and the shame of being perceived as weak or emasculated; those male victims may not disclose the abuse or seek help (Hogan et al. 2012). This, in turn, reinforces the silence and isolation of male victims, particularly during climate change events in the Caribbean.

To reduce the societal stigma associated with GBV against men and boys, there must be greater emphasis on changing social norms in the Caribbean by addressing harmful stereotypes about masculinity that discourage men from showing vulnerability during climate change events (IJC 2016). To do so, there are several avenues that private and public sector agencies in the Caribbean can pursue, such as (1) training personnel (case workers, psychosocial support staff, advocates, medical staff, legal professionals, and security staff) to respond, treat, and respect male victims without judgement, (2) creating awareness campaigns and education that normalize help-seeking behaviors for male victims, and which allow for easier engagement with men in communities, allowing them to become role models and advocates against such violence during/after climate change events, and (3) facilitating the creation of safe spaces for male victims during natural disasters to access confidential and non-judgmental support (Rechenberg et al. 2024; Ghosh and Kumar 2024).

6.2. Cultural Norms

It is often thought that female aggression is reflective of self-defense; however, such aggression has been linked to jealousy, anger, and punishment. In the case of men and boys, those who display male dominance are perceived as simply fulfilling societal expectations. This behavior is often linked to their status within the home, community, and workplace, as well as their self-esteem and sense of self-importance. For this reason, men and boys who go against these cultural norms when they become victims of GBV during climate change events may now be thought of as having undesirable traits such as being either weak or defenseless (Burcar 2013). This can encourage a cycle of controlling or fear-inducing behaviors with their partners, which may become a normal aspect of relations and continue after the threat of a natural disaster has passed (Gadd et al. 2003). These cultural norms frequently act as a barrier to GBV against men and boys, because they not only delegitimize their experiences, but the presence of hegemonic masculinity within society, which dictates their traits as being dominant, stoic, and unemotional, is also likely to pressure male victims to endure such violence (Majola et al. 2023).

To address the cultural norms aspect of GBV, there is a need for a multi-level effort that targets several different aspects of the unspoken rules of society, such as the values, beliefs, and social conventions that influence how society views and

relates to male victims during and after climate change events in the Caribbean. In this regard, several avenues can be taken, inclusive of (1) challenging gender roles rooted in historical patriarchy and masculinity that justify violence against men, (2) reshaping cultural expectations by encouraging and partnering with men and boys in communities and educators through social media to become allies against GBV that may occur during/after climate change events, and (3) encouraging women to address power imbalances that fuel GBV in the Caribbean (Dixit 2024).

6.3. Perception

Building on the previous two barriers, perception, as mentioned earlier, can become a significant barrier to the reporting of GBV against men and boys, as male victims may become reluctant to report such incidents. Such abuse, when instigated by female partners, can become increasingly complex, as according to Burcar (2013) male victims may not be willing to report such instances of abuse because it may give the impression that they have accepted their defeat and are no longer the ones in control of the situation. Such notions of male violence, even when taking place during and after climate change events in the Caribbean, have strong associations with stigma, as well as societal and cultural norms, because such norms strongly associate masculinity with strength, dominance, and emotional stoicism.

Male victims may be either discredited or devalued by partners or community members when they express feelings of vulnerability, and men and boys may be unaware that they too can be victims because the narratives presented in mainstream media and societal expectations typically reinforce the idea that women and girls are usually the victims of GBV during climate change events (Smee et al. 2022). Such divergences in the approach towards GBV, unfortunately, not only encourage male victims to hide their abuse experienced during and after climate change events, but diminish their willingness to access support services because they may not be aware of their rights, or their experience may be dismissed by service providers and law enforcement (Taylor et al. 2021).

A further barrier concerns the marketing of social and humanitarian services by the media during climate change events in the Caribbean. That is, in advertising and campaigns against domestic violence, males are often portrayed as the abusers, and females as the victims. In addition to this, men of different sexual orientations who have experienced domestic violence by their same-sex partners may not be represented in these awareness programs (Helman and Ratele 2018).

As discussed by Smee et al. (2022) and similarly to the other solutions put forward, to change the perceptions of persons towards violence against men and

boys in the Caribbean during and after climate change events, there is a need to create an emotionally and physically secure environment where male victims can express and reflect their feelings without fear of prejudice. Further to this, given that social media plays a significant role in reducing GBV through education and resource mobilization, emphasis should be placed on changing the narrative that the media portrays about GBV from one that typically impacts women and girls to one that emphasizes that GBV is a shared form of harm where both genders can be adversely affected and highlights the unacceptability of violence and abuse towards men and boys in the Caribbean during and after climate change events (Zinyemba and Hlongwana 2022). In addition to this, there is a need for the development of more inclusive programs that address the entire range of genders who experience GBV and not only women during instances of natural disasters in the Caribbean. This will transform GBV from being a female problem to one that reflects a gender conflict.

6.4. Security and Legislation

Security-related barriers can also function as a significant barrier to male victims in the Caribbean during and after climate change events because the heightened presence of security personnel during these events may deter male victims from reporting the crime they experienced, in addition to existing fears of abuse of power (Taylor et al. 2021). Such behavior implies that there are several factors in place, the first being that security personnel may lack the necessary training and expertise to respond appropriately to male victims, and as a result, their responses may be unsupportive and biased (UNHCR 2024). Second, male victims who become displaced during climate change in the Caribbean may experience additional security barriers, such as legal consequences, because male victimization may not be recognized by the judicial system (ICRC 2022).

In the case of the Caribbean, there are several countries such as Barbados, Belize, Bermuda, Guyana, Jamaica, and Saint Lucia that all have legal standards to protect victims of GBV; however, while these legal standards were designed and ratified by the International Human Rights Convention in the context of female victims, addressing a wide range of concerns such as domestic violence, stalking, and misconduct, and protection against such acts, there are very few provisions made specifically for male victims (UN Women 2021). A brief examination of the body of these legislative acts and offences shown in Table 1 below reveals that they are not gender-specific and can be accessed by all abused persons, regardless of gender, age, and nationality. However, within these acts, women and girls are often specified

as the primary victims, and not men and boys, because the reports and the persons accessing security and humanitarian services are often women and girls.

Although the GBV legislation in the Caribbean has often prioritized the protection of female victims due to the disproportionate impact of violence and abuse on them, male victims of GBV during and after climate change events can seek legal recourse against abusers and perpetrators under the guidance of these pieces of legislation, as they often include protection orders and other strategies that are gender-neutral (UN Women Caribbean n.d.). In addition, to further address male victimization, several countries in the Caribbean such as Guyana, Trinidad and Tobago, and the Bahamas have made revisions to their GBV and rape legislation to make these laws more gender-neutral, therefore recognizing and protecting male victims, as well as strengthened penalties for offences involving children (UN Women Caribbean n.d.).

Table 1. GBV legislation of selected Caribbean nations.

Selected Countries	Laws Implemented
Barbados	Domestic Violence Act 1992, Sexual Offences Act 1992, Offences against the Person Act Cap 141.
Belize	Domestic Violence Act 2007, Criminal Code 2000, Protection Against Sexual Harassment Act 1996.
Bermuda	Domestic Violence Act 1997, Criminal Act 1907, Criminal Code, Sexual Offences Amendment Act 1993, Criminal Code Amendment Act 2007, The Stalking Act 1997, The Stalking Amendment Act 1998.
Guyana	Domestic Violence Act 1996, Sexual Offences Act 2010 The Prevention of Discrimination Act 1997.
Jamaica	Domestic Violence Act 1995, Sexual Offences Act 2009 The Child Pornography Act 2009.
Saint Lucia	Domestic Violence Act, Criminal Code, Sexual Harassment.

Source: Author's compilation based on legislative information provided by UN Women (2021).

Despite the legislative changes made to protect male victims in the Caribbean, there are several avenues that policymakers can take to explicitly recognize and address the needs of male victims during and after climate change events. During and after climate change events, these specific measures can include the following: (1) Amending laws to explicitly include not only male victims but those of either a different sexual orientation or non-traditional relationships so that all forms of violence can be addressed regardless of the victims' gender. (2) Even though

gender-neutral laws are useful, they are often limited in the sense that they may overlook the gender-specific needs of victims, which can reinforce harmful stereotypes, systemic inequality, and their overall effectiveness, as they may be misinterpreted and applied inconsistently; instead what is needed are specific pieces of legislation to address the gendered nature of violence that is likely to occur during natural disasters in the Caribbean to encourage male victims to report its occurrences. Finally (3) closing the gaps between the design and implementation of legislation in the Caribbean by providing sufficient resource funding for GBV against men and boys response programs and training for all stakeholders (medical, security, and legal staff) to reduce stigma and bias, as well as support services (legal aid, counseling, and shelters) that are intentionally created for male victims (EU 2022; OECD 2023).

7. Conclusions

Climate change is important because it affects various aspects of our lives, from health and the environment to social and economic well-being. Taking action to address climate change is essential for a sustainable and resilient future because it not only reduces the death of persons resulting from extreme climate change events, but also limits the spread of diseases, sustains the production of food, and may positively alter the balance of ecosystems, leading to the preservation of animal and plant species around the world. Despite the positive actions in dealing with the adverse effects of climate change, the type and intensity of climate change events may deepen social and economic inequalities, leading to the displacement of vulnerable persons.

In this chapter, the discussion is focused on the nuanced ways in which climate change events in the Caribbean region are likely to exacerbate the hardships faced by male victims of gender-based violence (GBV), such as domestic violence. To do this, it sheds light on the significant inequalities that men and boys, particularly those that may be considered vulnerable, i.e., the disabled, elderly, and those living in low-income households, may experience in terms of accessing and utilizing vital resources, as well as their risk of experiencing GBV at the hands of partners, community members, household members, and friends. The disparities faced by men and boys who are victims of GBV can be further intensified because the traditional roles and social expectations rooted in patriarchal structures in the Caribbean often reinforce power imbalances, normalize violence, and force rigid ideals of masculinity and emotional suppression amongst men and boys. In instances where male victims of GBV go against these masculine ideals, not only can their vulnerability and passiveness lead to feelings of isolation and inadequacy, as well as mental health issues such as anxiety, depression, and suicide, but it may perpetuate harmful

stereotypes in society, which may worsen existing societal ills such as poverty, conflict, and displacement.

In the context of the presence and intensification of climate change events in the Caribbean, men who possess financial resources, education, and specialized training may find that climate change events have minimal repercussions on their daily lives. This resilience can be attributed to their ability to employ effective mitigation and adaptation strategies, such as diversifying income sources, investing in sustainable practices, or accessing community resources. However, the same cannot be said for male victims of GBV, as the inability of male victims to effectively cope with these masculine ideals under severe climate change conditions can push them into desperate situations, which may lead to their heightened vulnerability to different forms of abuse/violence. Under the circumstances of climate change-related displacement, together with insufficient laws and weak legislative enforcement to protect against discrimination and inequality in the Caribbean, instances of economic hardship can reduce male victims' access to education, employment, and social protective services. Such resource scarcity, which is often exacerbated by climate change events, may also lead to male victims in the Caribbean facing an increased risk of violence, as these events may create the conditions where GBV is more likely to occur, especially in economically unstable households. Vulnerable men in the Caribbean who lack the advantages of those who may be financially secure may struggle to cope with the increased stresses brought on by climate-related disasters, which can further perpetuate cycles of violence and marginalization. It is at this point that the intersection of climate change and GBV underscores the critical need for inclusive policies that consider the unique challenges faced by male victims in the context of environmental shifts and natural disasters.

Climate change can not only be linked to a rise in male cases of victimization as extreme weather events increase in the Caribbean, but can also lead to a growth in physical, emotional, and verbal abuse of vulnerable men. Vulnerable male victims, like female victims in similar situations, are also responsible for taking care of their families during and after climate change events. Given that GBV acts can be used by the male victim's partners, community and household members, and friends to exert control over the victim's access to resources, it is important in the Caribbean to (1) provide more education and information for male victims through communication media and NGO partnerships to encourage greater awareness, (2) change how men are viewed culturally and within society to promote more positive images of masculinity and male vulnerability, and (3) encourage policymakers to adopt more male-sensitive strategies in their climate change mitigation and adaptation plans, as

well as in their GBV legislation, to reduce discrimination and inequality, so that all perpetrators can be held accountable, and all male victims have access to shelters and support services.

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Towards a Climate-Resilient World: The Role of Renewable Energy, Innovation, and High-Tech

Pascaline Nyirabuhoro and Jean Claude Ndayishimiye

1. Introduction

One avenue through which current global issues can be mitigated is through innovations and high-tech solutions, which reduce reliance on conventional power sources and lower GHGs (Anderson and Rezaie 2019; Killingtveit 2019; Kannan and Vakeesan 2016; Archer and Jacobson 2005). Innovation has been crucial in shaping human development, particularly in addressing complex societal challenges during the Industrial Revolution (Lundgren 1995). The impact of innovation extends not only across key economic sectors such as healthcare, education, and industry but also in addressing critical issues such as the energy crisis, pollution, extreme weather, and disasters (Izumi et al. 2019; Desrochers 2001; Lundgren 1995). Nevertheless, the problem-solving potential of technology is inherently tied to innovation, making innovation and high-tech intertwined forces in shaping human development (Kline and Rosenberg 2010). All of these require close coordination of sufficient technical knowledge and excellent market judgment to address constraints (Kline and Rosenberg 2010; Desrochers 2001). Moreover, the diverse spectrum of environmental challenges, each characterized by its own unique attributes, demands context-specific innovative and high-tech solutions, thereby intensifying the complexity of the overall approach (Desrochers 2001). With advancements in science and research, a clearer understanding of the most effective innovation and high-tech pathways, particularly in addressing global change, is expected to emerge (Kline and Rosenberg 2010).

Climate change, an incontrovertible consequence of industrialization, has become one of the most pressing global risks affecting both development and health (Richardson et al. 2011). The Earth's climate is experiencing notable transformations, characterized by rising temperatures, alterations in precipitation patterns, and a surge in extreme weather events (Seneviratne et al. 2021). Human activities, notably the combustion of fossil fuels, deforestation, and industrial processes, are the main drivers of climate change. The emission of GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), intensifies the natural greenhouse

effect, trapping heat within the Earth's atmosphere (Stern and Kaufmann 2014). The increased GHGs further result in planetary warming, causing disruptions to natural climate cycles and amplifying the impacts of climate extremes on ecosystems and human societies (Seneviratne et al. 2021; Stern and Kaufmann 2014). Mitigating climate change is a complex challenge due to various interconnected factors that contribute to GHG emissions and global warming (Ali and Mujeeb-Kazi 2021; van Kooten 2018; Princiotta 2009). The global economy has long been reliant on fossil fuels, such as coal, oil, and natural gas, for industrial production and trade (Wang et al. 2022a). Transitioning away from these conventional sources requires changes in economic and infrastructural systems, making the shift to a carbon-neutral economy a formidable task (Tollefson 2018; Tomczak 2005). Therefore, the pressing need to address climate change raises a fundamental question: can the world rapidly break free from its addiction to fossil fuels? This underscores the importance of evaluating the speed and effectiveness of global efforts to transition towards renewable energy sources (Tollefson 2018).

In the current epoch marked by anthropogenic climate change, sustainable technologies stand as crucial catalysts for positive transformation (Mulder et al. 2017; Weaver et al. 2017). Built upon the principles of minimizing environmental impact, preserving resources, and fostering long-term ecological balance, sustainable technologies prioritize energy efficiency, the use of renewable resources, and waste reduction. These principles guide the use of technologies to meet present needs without limiting the ability of future generations to meet theirs (Abraham 2017). A major impact of sustainable technologies is evident in the field of energy, where innovation and high-tech solutions have enabled enterprises to shift the global landscape from agricultural to industrial-driven economies (Anderson and Rezaie 2019; Killingtveit 2019; Kannan and Vakeesan 2016; Archer and Jacobson 2005). However, uncertainty persists about how technology can effectively address more complex global issues, particularly those related to industrial emissions and climate change (Mulder et al. 2017; Weaver et al. 2017). This underscores the necessity for thorough evaluation, ensuring that sustainable technologies contribute effectively to addressing multifaceted environmental challenges over time.

Investigation into the fields of innovation, high-tech, and renewable energy lays the foundation for a deeper understanding of the complex interplay between technological development and climate resilience worldwide (Xie et al. 2021; den Elzen et al. 2013). This paper thoroughly reviews how technological advancements boost the consistent use of various renewable power sources, providing economically reliable solutions that address both the energy crisis and climate change over time.

This approach involves evaluating existing power systems, capacities, and priorities for advancement in the renewable energy sector (Figure 1). The overarching aim of this review is to demonstrate the central role of innovation in the renewable energy sector in building a climate-resilient world and achieving sustainable development goals. The expected outcomes encompass a better understanding of the intricacies of innovation, renewable energy, and climate change, along with inspiring solutions for a future marked by sustainability, resilience, and environmental harmony.

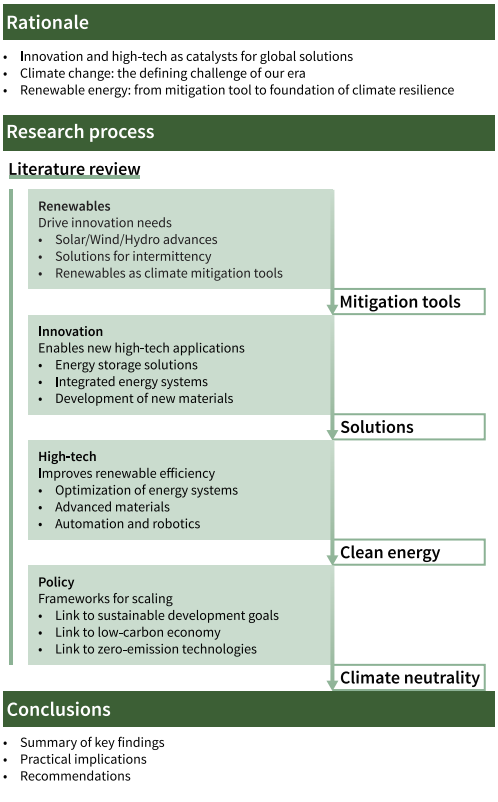


Figure 1. The study framework. Source: Figure by authors.

2. Solar Power

2.1. Strategic Role of Solar Power in Mitigating the Energy Crisis and Addressing Climate Change

The distribution and availability of sunlight, considering factors such as insolation, cloud cover, and land, are sufficient to meet the global annual demand

for electricity (Figure 2a). The total global annual solar energy potential ranges from 1575 to 49,837 EJ, equivalent to 4.37×10^{17} and 1.384×10^{19} kWh, respectively.

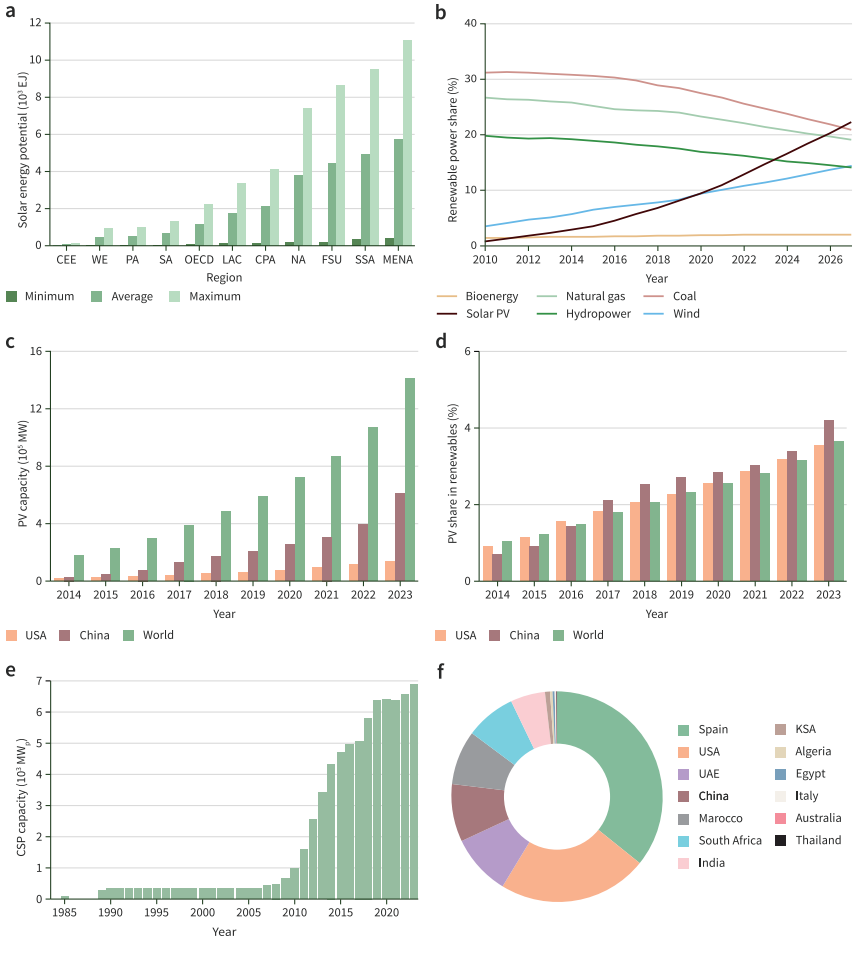


Figure 2. Global solar energy, depicted through (**a**) solar energy potential, (**b**) trends in renewable power, (**c**,**d**) trends in solar PV, and (**e**,**f**) trends in CSP. Source: Authors' compilation based on data from IRENA (2024), IEA (2022b), REN21 (2014, 2016, 2017, 2018), CSP World (2013), Goldemberg (2000), and Nakićenović et al. (1998).

The early development of solar technology was motivated by the expectation of a future scarcity of coal (Mouchot 1869). Nevertheless, such development slowed in the early 20th century due to the growing availability, cost-effectiveness, and utility of coal and petroleum (Butti and Perlin 1981). The 1973 oil embargo and

the 1979 energy crisis drove a global reevaluation of energy policies, leading to renewed interest and investment in developing solar technologies. During this period, new strategies, including incentive programs such as the Federal Photovoltaic Utilization Program in the USA (Hart 1983) and the New Sunshine Program in Japan (Tatsuta 1996), as well as the establishment of research institutions such as the Energy Research Institute (now the National Renewable Energy Laboratory) in the USA, the New Energy and Industrial Technology Development Organization in Japan, and the Fraunhofer Institute for Solar Energy Systems in Germany, played a pivotal role in advancing solar technologies (Yergin 1991; Butti and Perlin 1981). In the current global pursuit of transitioning to sustainable energy sources and addressing the challenges of climate change, solar power (Figure 2b) emerges as a pivotal solution (Li et al. 2022; Kannan and Vakeesan 2016). Solar systems tested in both developing and industrializing nations have demonstrated the practicality of reducing dependence on fossil fuels as a primary source of energy (Bulut and Menegaki 2020; Ho et al. 2019). For instance, the Bhadla Solar Power Plant (Figure 3), situated in the Thar Desert of Rajasthan, India, holds the distinction of being the largest solar power plant in the world, with a remarkable installed capacity of 2245 MW. Covering an area of 56 km^2, the plant generates around 732,874 MWh of electricity annually, which is sufficient to power more than 1 million homes. With over 10 million solar panels in operation, Bhadla Solar significantly contributes to environmental sustainability by reducing CO_2 emissions by approximately 694,471 t each year (Kumar 2022a). In Rwanda, a landlocked nation experiencing a rapid change in local weather patterns due to climate change and with people heavily depending on biomass as their primary energy source in cooking (Hakizimana 2022), a power station comprising 28,360 individual PV panels spread across a 20 ha field was connected to the national electricity grid in September 2014. This power plant operates at a maximum capacity of 8.5 MW, taking advantage of the abundant solar radiation prevalent in the country, which typically surpasses the recommended 3.6 kWh $m^2 \cdot d^{-1}$ for solar PV installations (Ukwishaka et al. 2021). The environmental and economic implications of this power plant clearly establish solar energy as a promising source with the potential to significantly reduce dependence on both biomass and fossil fuels while simultaneously addressing local weather patterns (Hakizimana 2022). Therefore, solar energy emerges as a clean and renewable power source, demonstrating success in generating electricity without emitting GHGs while simultaneously contributing to climate change mitigation (Bulut and Menegaki 2020; Ho et al. 2019).

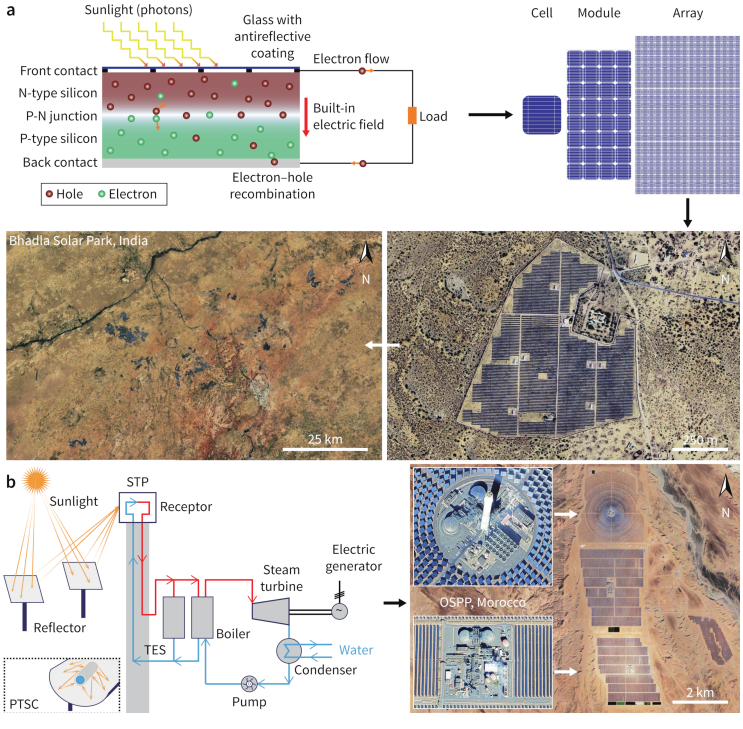


Figure 3. Schematic diagrams and satellite imagery of (**a**) solar PV systems and (**b**) CSP systems. Source: Authors' compilation based on data from Ziabari (2025), Enescu et al. (2020), and Jean et al. (2015).

2.2. Solar Power Systems and Priorities for Modernization

Solar power systems (Figure 3) represent diverse technological solutions that capture sunlight to generate usable electricity or heat for various applications, with each type distinguished by specific features (Table 1). This versatility extends from small-scale residential use to large-scale utility installations, offering innovative solutions for different needs. Examples include solar PV systems, such as residential rooftop panels (Figure 3a), solar thermal systems for residential water heating, CSP systems in utility-scale installations (Figure 3b), off-grid solar systems for remote locations, grid-tied solar systems in commercial setups, building-integrated PV in structures, solar street lighting systems for urban areas, floating solar farms on water bodies, portable solar systems for outdoor activities, and solar-powered vehicles such as cars or electric bicycles.

Table 1. Characteristics of solar power systems.

Layout			Operational Dynamics			Upcoming Breakthroughs		References
Name	Description	Components	Capacity	Applications	Challenges	Technical	Sustainability	
PV	Converts sunlight into electricity via solar cells	Solar cells, inverters, mounting structures, and batteries	250–2245 MW	Residential, commercial, utility-scale, and off-grid power solutions	Sunlight-dependent, storage limits, land use, and high initial cost	Efficiency, storage, and grid integration	Manufacturing, recyclable materials, and disposal management	Benjamins et al. (2024), Kumar (2022a), Tawalbeh et al. (2021), Obeidat (2018), and Lupangu and Bansal (2017)
CSP	Uses concentrated sunlight to produce heat for electricity generation	Mirrors/lenses, receivers, turbines, and thermal energy storage	<1–510 MW	Utility-scale power generation, industrial processes, and desalination	High land usage, water consumption, and high initial costs	Efficiency in concentration and energy storage	Water-saving technologies and eco-friendly material sourcing	Alami et al. (2023), Xu et al. (2022), Wilson et al. (2020), Ehtiwesh et al. (2016), Otieno and Loosen (2016), and Jelley and Smith (2015)
Solar water heating	Absorbs sunlight to heat water or fluid	Solar collectors (flat-plate or evacuated tube), pumps, and controllers	1.5 kW–110 MW	Residential hot water, commercial processes, and swimming pool heating	Sunlight dependency, space requirements, and high initial costs	Thermal storage and collector efficiency	Sustainable materials and integration with existing systems	Fadzlin et al. (2022), Tschopp et al. (2020), Ahmed et al. (2021), Wang et al. (2015), Islam et al. (2013), and Shukla et al. (2013)
Solar cooking	Uses solar energy to cook food by concentrating sunlight	Reflective surfaces, insulation, adjustable supports, and cooking pots	0.5 kW–50 kW	Household cooking, outdoor cooking, and community kitchens	Weather-dependent, slow cooking, and limited cooking styles	Reflector/absorber design and cooking time reduction	Cost-effective manufacturing and increased accessibility	Ceviz et al. (2024), Saxena et al. (2022), Singh (2021), Ghodbane et al. (2020), and Panwar et al. (2012)

Table 1. *Cont.*

Layout			Operational Dynamics			Upcoming Breakthroughs		References
Name	Description	Components	Capacity	Applications	Challenges	Technical	Sustainability	
Solar desalination	Converts saline water into freshwater using solar energy	Solar collectors and desalination technologies (reverse osmosis and distillation)	5 $L \cdot d^{-1}$–3.4 × 10^6 $m^3 \cdot d^{-1}$	Drinking water supply, irrigation, and emergency relief	Energy-intensive, weather-dependent, and brine disposal issues	Desalination efficiency and energy integration	Eco-friendly brine disposal and scalable solutions	Al-Buraiki et al. (2024), Khashehchi et al. (2024), Ihsanullah et al. (2021), El-Bialy et al. (2016), and El-Sebaii and El-Bialy (2015)
Solar lighting	Uses solar energy to power light sources (light-emitting diodes and streetlights)	PV cells, charge controllers, light-emitting diodes, and batteries	1–250 W	Outdoor lighting, street lighting, rural lighting, and emergency lights	Weather dependency, initial costs, and battery replacement	Panel efficiency, battery longevity, and smart controls	Sustainable battery materials and recyclable components	Ciriminna et al. (2017), Pode and Diouf (2011), and Faranda and Fumagalli (2008)
Solar ventilation	Uses solar power to operate ventilation systems	Solar-powered fans, thermal chimneys, and sensors	50–50,000 $m^3 \cdot h^{-1}$	Residential, commercial, agricultural, and off-grid ventilation	Sunlight dependency, space requirements, and efficiency in extreme conditions	Fan design, energy storage, and compact systems	Eco-friendly materials and system longevity	Zhang et al. (2022), Imran et al. (2015), and Harris and Helwig (2007)
Solar charging stations	Use solar energy to charge electric vehicles and devices	Solar panels, inverters, charge controllers, and batteries	0.5–>5 MWh	Electric vehicle charging, device charging, and off-grid solutions	Sunlight dependency, space constraints, and energy storage challenges	Enhance solar panel efficiency and fast-charging technology	Scalable designs, sustainable materials, and grid integration	Balal and Giesselmann (2024), Maddilety et al. (2024), Yap et al. (2022), Ghodusinejad et al. (2022), and Goldin et al. (2014)

Lower values of estimated capacity correspond to small-scale applications, while higher values correspond to large-scale applications.
Source: Table by authors.

The attractiveness of solar power systems, particularly in the form of solar panels for electricity generation, stems from a confluence of numerous factors. Environmental benefits, notably the reduction in waste and emissions, make them a sustainable and eco-friendly choice (Ahmadi et al. 2018; Faiers and Neame 2006). Technological advancements continuously boost the efficiency and effectiveness of these systems, contributing to their long-term viability and competitiveness in the energy sector (Rathore et al. 2021; Nayak et al. 2019; Bahrami et al. 2013). Governmental funding initiatives further bolster the appeal of solar power systems by providing financial support and incentives, encouraging widespread adoption and investment (Corwin and Johnson 2019). CSP and solar thermal systems for electricity generation attract considerable attention, particularly in large-scale industrial projects. These systems expand the potential applications of solar power, meeting a wide range of energy demands in both utility-scale and industrial settings (He et al. 2020; Gonzalo et al. 2019; Răboacă et al. 2019). Nevertheless, the inherent intermittency of solar resources poses challenges for grid reliability (Kong et al. 2020; Sharma et al. 2020). The integration of energy storage systems with solar power systems effectively mitigates this limitation, enabling dispatchable power generation and facilitating smoother grid integration (Tan et al. 2021).

Despite their immense potential, solar power systems encounter challenges that impede their widespread adoption (Table 1). The dependence on sunlight for electricity generation presents intermittency and weather dependence, requiring effective energy storage systems to ensure consistent production. Large-scale installations face concerns over land use, habitat disruption, and esthetic objections, while the production of solar panels relies on materials with environmental and geopolitical implications. High upfront costs hinder broader adoption, underscoring the need for strategies to reduce initial investments. Moreover, energy storage systems, though improving, require technological advancements to address cost, efficiency, and environmental impact concerns (Kong et al. 2020; De Castro et al. 2013; Verbruggen et al. 2010). Key challenges in solar energy are being addressed through focused innovation and high-tech solutions in (1) advanced energy storage technologies for creating efficient, cost-effective, and environmentally friendly energy storage systems; (2) smart grid integration to enhance the incorporation of solar power into existing energy infrastructures; (3) innovations in PV technologies aimed at making solar power more competitive with conventional energy sources; (4) solar solutions for urban spaces to address land use concerns and promote solar integration in densely populated areas; and (5) circular economy approaches to minimize

environmental impacts and reduce the industry's dependence on scarce resources (Table 1).

2.2.1. Solar PV Systems

PV cells, commonly referred to as solar cells (Figure 3a), are at the forefront of renewable energy development (Rathore et al. 2021; Nayak et al. 2019; Bahrami et al. 2013). These innovative devices directly convert sunlight into electricity, offering a clean and sustainable power source (Rathore et al. 2021). Operating on the principle of the photoelectric effect, initially developed by Albert Einstein, PV cells release electrons from the semiconductor material within the cell when struck by sunlight composed of photons (Figure 3a), thereby generating an electric current (Nayak et al. 2019). The core component of a PV cell resides in the semiconductor materials, typically made from crystalline silicon or other compound semiconductors (Nayak et al. 2019; Jordehi 2016; Bahrami et al. 2013). These materials significantly influence the efficiency and cost-effectiveness of the cell, with silicon dominating the market due to its abundance and reliability (Sultan et al. 2020; Peake 2018). PV cells feature a P-N junction, where positively doped (P-type) and negatively doped (N-type) semiconductors meet (Figure 3a). This junction creates an electric field that facilitates the flow of electrons, resulting in the generation of an electrical current when exposed to sunlight (Bahrami et al. 2013).

Various types of PV cells exist; however, monocrystalline silicon, polycrystalline silicon, and thin film dominate the global market (Nayak et al. 2019; Peake 2018; Bahrami et al. 2013). Tandem solar cells and perovskite solar cells are poised to become conventional and cost-effective materials for solar energy applications, but their widespread adoption hinges on overcoming stability and scalability challenges (Li et al. 2020; Li and Zhang 2020; Wali et al. 2018). Additionally, advancements in flexible and transparent PV technologies are expanding solar applications, integrating solar panels into everyday surfaces such as windows, clothing, and portable devices (Kim et al. 2021; Pulli et al. 2020).

Solar PV is projected to become the world's largest power source, surpassing coal in installed power capacity by 2027 (Figure 2b). Notably, China, the global leader in industrial output, has emerged as the world's largest installer of solar PV in recent years (Figure 2c,d). In 2018, China accounted for 6% of global solar PV module production, and within its borders, the Tengger Desert was home to the world's largest PV plant (Kumar 2022b). That year, China added an impressive 44,215 MW of installed PV capacity, and by 2022, its share in solar panel manufacturing surpassed 80% across all production stages. The transition to solar energy has

also been significant in the USA (Figure 2c,d), with installed capacity increasing from 16,445 MW in 2014 to 137,725 MW in 2023. This trend is not limited to industrial powerhouses; emerging economies such as Chile, Jordan, and Honduras are also expanding their solar energy adoption, contributing to the global energy transition toward complete reliance on renewable sources by 2050 (Ram et al. 2020).

2.2.2. CSP Systems

CSP systems (Figure 3b) represent an advanced tool for capturing solar energy for electricity generation (Alami et al. 2023; Xu et al. 2022; He et al. 2020; Wilson et al. 2020; Relloso and Gutiérrez 2017; Ehtiwesh et al. 2016; Otieno and Loosen 2016; Jelley and Smith 2015). At their core is the principle of concentrating sunlight to generate heat, which is then used to produce electricity (Răboacă et al. 2019). Vital components include mirrors or lenses that focus sunlight onto a small area, generating intense heat. This thermal energy is transferred to a working fluid, such as molten salt or oil, which is then used to generate steam. The resulting steam drives turbines connected to generators, ultimately producing electricity (He et al. 2020; Gonzalo et al. 2019; Răboacă et al. 2019). Productivity hinges on key factors such as sunlight concentration, working fluid choice, and the conversion of heat into electricity.

As of 2023, the global installed CSP capacity stood at 6876 MW (Figure 2e), largely due to new projects in the UAE. Spain remains the largest CSP contributor, accounting for nearly one-third of the world's capacity (2300 MW), though no new capacity has been added since 2013. The USA follows with 1740 MW, and increasing interest is observed in Southern and Northern Africa, Southeast Asia, and Oceania, where high solar radiation favors CSP development (Figure 2f). Despite its advantages, CSP capacity remains significantly lower than that of PV systems, which reached 1412.1 GW in 2023 (Figure 2c). This difference is largely due to the declining costs of PV systems, which influence market dynamics and the competitiveness of CSP. Utility-scale CSP plants are approximately five times more expensive than PV power stations, with advanced CSP systems costing at least 7% per kWh, compared to PV's record-low 1.32% per kWh. Additionally, CSP presents environmental challenges, particularly in terms of water consumption, land use, and hazardous material handling. For instance, CSP plants with wet cooling consume 3.1 $m^3 \cdot MWh^{-1}$ (power towers) and 3.4 $m^3 \cdot MWh^{-1}$ (trough systems), higher than nuclear (2.7 m^3 MWh^{-1}), coal (2.0 $m^3 \cdot MWh^{-1}$), or natural gas (0.79 m^3 MWh^{-1}) plants with cooling towers (Meldrum et al. 2013).

2.2.3. Passive Solar Systems

Temperature is expected to rise significantly by 2050, particularly during the summer (Cubasch et al. 2001). The existing housing infrastructure is expected to be insufficient to address this changing climate scenario effectively, leading to a surge in cooling energy consumption and a range of health and comfort-related issues (Suárez et al. 2018). Passive solar systems, designed for space heating and cooling to enhance thermal comfort in buildings, present an opportunity for climate change mitigation by reducing reliance on conventional energy sources (Silva et al. 2022). These systems involve various architectural and design features that enable the utilization of sunlight without the need for active mechanical and electronic devices (Eicker 2003; Anderson and Michal 1980). There are several types of passive solar technologies, with commonly used ones including direct gain, indirect gain, isolated gain, Trombe walls, and thermal mass (Akaf et al. 2019). These technologies effectively transform sunlight into usable heat, which is stored in water, air, or thermal mass, facilitating air movement for ventilation or future use while minimizing dependence on additional energy sources (Chan et al. 2010). For space heating and cooling, these systems involve designing windows, walls, and floors to capture, store, reflect, and disperse solar energy—retaining heat in cold conditions and deflecting it in warm conditions (Anderson and Michal 1980). Thus, designing an effective passive solar building relies on maximizing the benefits of the local climate; key considerations include window placement and size, glazing type, thermal insulation, thermal mass, and shading (Liu et al. 2018). Notably, passive solar technologies are versatile and can be applied not only to newly constructed buildings but also to existing ones through retrofitting (Eicker 2003; Anderson and Michal 1980).

Passive solar technologies are widely used in both residential and commercial buildings, contributing to energy efficiency and sustainability (Eicker 2003). They serve multiple functions, including space heating, which utilizes sunlight to warm indoor spaces during colder periods; daylighting, which maximizes natural light to reduce reliance on artificial lighting; natural ventilation, which enhances airflow for cooling without mechanical systems; solar water heating, which employs solar energy to heat water for domestic or industrial use; and passive cooling, which entails designing structures to minimize heat gain and improve cooling (Chan et al. 2010). Despite their benefits, passive solar systems have certain drawbacks (Eicker 2003). These include dependence on climate, variable effectiveness depending on geographical location and climate, design challenges that require careful integration of architectural elements, high initial costs due to specialized design features, and retrofitting challenges that make it more complex to adapt existing structures

compared to new builds (Akaf et al. 2019; Liu et al. 2018). Modernizations of passive solar systems seek to overcome these limitations (Chan et al. 2010; Anderson and Michal 1980). Strategies include incorporating sensors and automation for optimal energy utilization in building design, utilizing advanced materials with improved thermal properties, exploring nanotechnology for enhanced energy capture and storage, and integrating passive solar systems with other renewable technologies for comprehensive energy solutions (Akaf et al. 2019; Eicker 2003; Anderson and Michal 1980). These approaches are expected to foster a more resilient and eco-friendly energy landscape, significantly reducing GHG emissions and helping to mitigate climate change (Silva et al. 2022).

3. Wind Power

3.1. Strategic Role of Wind Power in Mitigating the Energy Crisis and Addressing Climate Change

Environmental awareness and the recognition of the impacts of burning fossil fuels gained global traction during the 1970s (Şahin 2004). Wind power emerged as a promising solution due to its potential to generate electricity without emitting GHGs (Archer and Jacobson 2005). In the 1980s and 1990s, notable technological advancements were achieved in the design and efficiency of wind turbines (Archer and Jacobson 2005; Şahin 2004). Many governments worldwide invested in research, leading to the development of more reliable and cost-effective wind power systems. This period witnessed the establishment of the first large-scale wind farms in different countries (Timilsina et al. 2013). In the early 2000s, many governments began implementing supportive policies and incentives to promote the use of renewable energy, including wind power. The introduction of subsidies, tax credits, and feed-in tariffs acted as catalysts for the development of wind projects, playing a pivotal role in enhancing the economic competitiveness of wind energy compared to conventional power sources. The 2010s were marked by exponential growth in the installed capacity of wind turbines, with onshore and offshore wind farms (Figure 4) becoming increasingly common. During this period, governments played a key role by setting ambitious renewable energy targets, further propelling investments in wind power infrastructure (Timilsina et al. 2013; Saidur et al. 2010).

As global installed wind power capacity expands (Figure 5a), a corresponding reduction in GHG emissions becomes increasingly plausible (Oliveira et al. 2019). Wind power is expected to achieve economic competitiveness with conventional energy sources by 2027, making it the second-preferred option for renewable energy after solar power (Figure 2b). By displacing electricity generation from fossil fuel

sources, especially coal and natural gas, wind energy will significantly contribute to a reduced overall carbon footprint in the energy sector, ultimately playing an important role in climate change mitigation (Barthelmie and Pryor 2014). Advances in energy storage and grid integration are expected to enhance the reliability and stability of wind power, leading to a more consistent and dependable energy supply (Ahmed et al. 2020; Zhao et al. 2015). Smart grid technologies will enable better management of intermittent wind resources, ensuring seamless integration into existing energy grids (Bayindir et al. 2016). Additionally, international collaboration through agreements such as the Paris Agreement is strategically driving wind energy technologies beyond advancements made before 2015. This, in turn, supports climate neutrality by utilizing clean energy, aligning with a comprehensive strategy aimed at limiting global warming to well below 2 °C above pre-industrial levels (Baruch-Mordo et al. 2019).

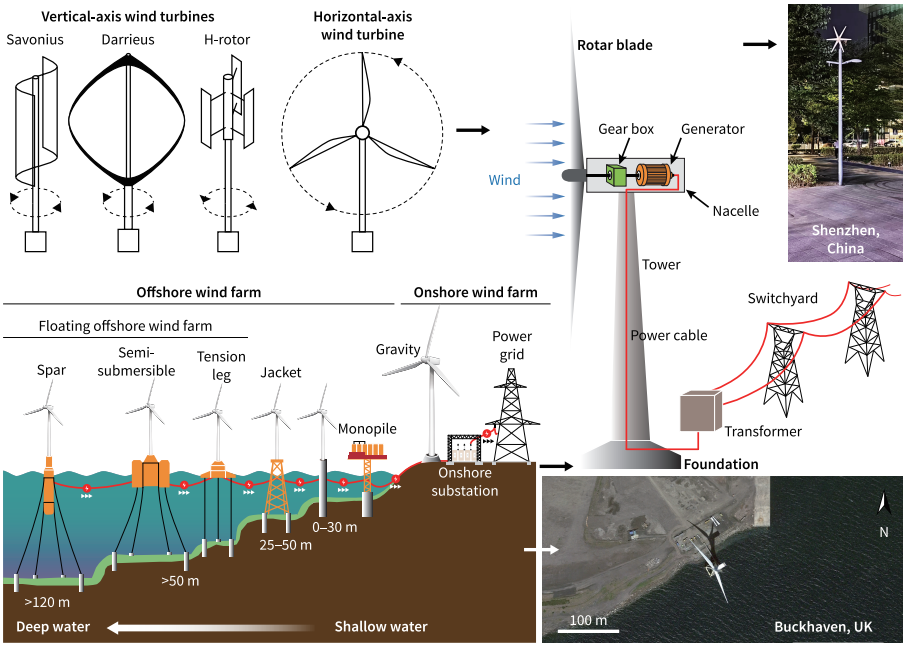


Figure 4. Schematic diagrams and photos of wind power systems. Source: Figure by authors.

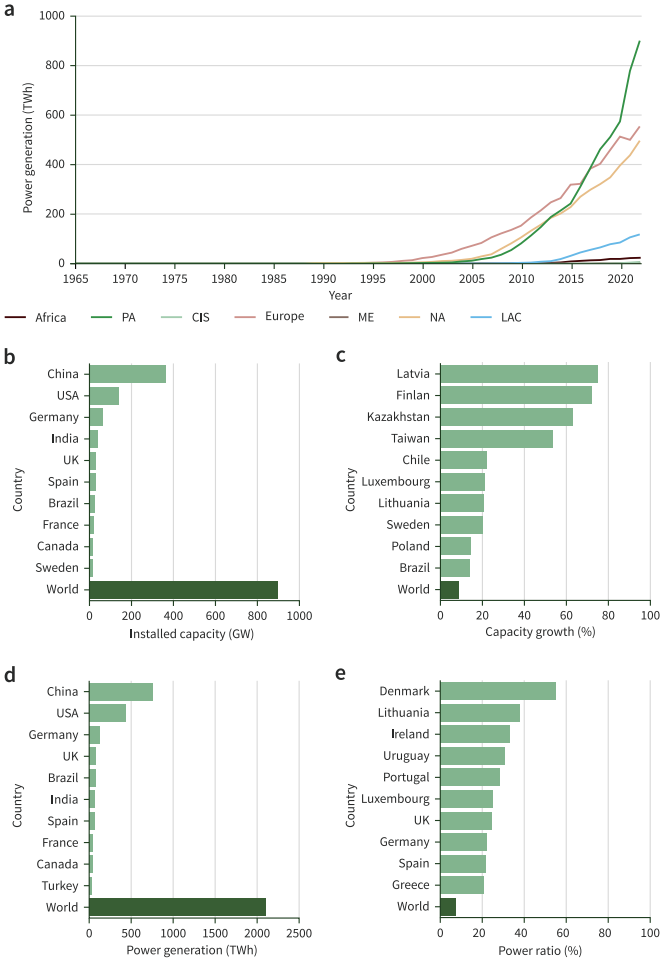


Figure 5. Global wind energy developments depicted by (**a**) trends in power generation, (**b**) power capacity, (**c**) power capacity growth, (**d**) power generation by major energy-producing economies, and (**e**) power dominance among top clean energy-producing economies. Source: Authors' compilation based on data from Ember (2023).

3.2. Wind Power Systems and Priorities for Modernization

3.2.1. Wind Power Systems: Historical Background and Types

Wind power has a rich history dating back thousands of years (Ragheb 2017). Its earliest recorded use can be traced to ancient civilizations, where wind energy

was employed for diverse purposes, including powering sailboats and operating windmills and windpumps (Lucas 2006; Al-Hassan and Hill 1986). The late 19th century marked the onset of the modern era of wind power, characterized by the development of windmills for electricity generation (Price 2005). However, it was not until the 1973 energy crisis that wind power regained attention. This crisis prompted research efforts in different countries, including Denmark, Spain, and the USA, leading to the development of larger utility-scale wind generators capable of connecting to electric power grids for remote power usage (Şahin 2004). Currently, wind-powered generators operate across a broad spectrum, ranging from small installations designed for battery charging at isolated residences to offshore wind farms with gigawatt-scale capacity that supply electric power to national electrical networks (Archer and Jacobson 2005; Şahin 2004). Notably, governments worldwide have increasingly invested in wind energy as a feasible alternative to fossil fuels (Saidur et al. 2010). Different wind power systems (Figure 4 and Table 2) have been developed for generating electricity; however, horizontal-axis wind turbines continue to be the most commonly used type (Schaffarczyk 2020; Óskarsdóttir 2014). These turbines are preferred for both offshore and onshore wind farms, particularly in areas with flat and open landscapes, because they offer greater efficiency compared to vertical-axis wind turbines, especially in regions with less turbulent wind (Schaffarczyk 2020; Óskarsdóttir 2014). Horizontal-axis wind turbines capture wind energy using blades mounted on a horizontal shaft, converting the resulting rotational motion into electricity through a connected generator (Schaffarczyk 2020).

The global cumulative installed capacity and electricity generation from wind power have surged since the beginning of the 21st century, reaching 898.86 GW and 2098.46 TWh by the end of 2022, respectively (Figure 5). Since 2010, more than half of new wind power additions have occurred outside the traditional markets of Europe and North America, with substantial contributions from China and India in Asia, as well as Brazil in South and Central America (Figure 5b–e). By 2022, China alone accounted for 40.71% of the world's wind power capacity (Figure 5b). Latvia recorded the largest percentage increase in wind capacity in 2022, growing by 75% (Figure 5c). The global share of electricity from wind power in 2022 was 7.3%, reflecting a slight decrease from 8.9% in the previous year. In Europe, wind power contributed 11.2% of electricity generation, with Denmark leading in 2022 by producing 55% of its electricity from wind (Figure 5e).

Table 2. Characteristics of wind turbine systems.

Layout			Operational Dynamics			Upcoming Breakthroughs		References
Name	Description	Components	Capacity	Applications	Challenges	Technical	Sustainability	
Horizontal-axis wind turbine	Rotor aligned parallel to wind direction; blades rotate around a horizontal axis; components: rotor, generator, tower	Optimized blade aerodynamics, pitch/yaw controls, smart grids, and advanced materials	0.45–252 MW	Offshore and onshore wind farms	Environmental impact (bird/bat collisions), noise, esthetics, and sensitivity to turbulent wind	Blade design, noise reduction, advanced control systems, and smart grid integration	Energy storage, grid stability, and eco-friendly materials	Farina and Anctil (2022), Qi and Gao (2020), Ahmed and Cameron (2014), and Óskarsdóttir (2014)
Vertical-axis wind turbine	Rotor perpendicular to wind; blades rotate around a vertical axis; components: rotor, generator, support structure	Helical/straight blades, adaptive control systems, and compact design	224–625 kW	Residential and commercial uses, off-grid locations, and solar hybrid systems	Lower efficiency, structural challenges, and blade proximity concerns	Aerodynamics, lightweight materials, noise reduction, and smart grid integration	Durability, weather resistance, and sustainable manufacturing	Farina and Anctil (2022), Arredondo-Galeana and Brennan (2021), Hui et al. (2019), Möllerström et al. (2019), and Óskarsdóttir (2014)

The estimated capacity of a vertical-axis wind turbine corresponds to small-scale applications, while the estimated capacity of a horizontal-axis wind turbine corresponds to large-scale applications. The horizontal-axis wind turbine is the more prevalent type, while the vertical-axis wind turbines are less efficient and less common (Óskarsdóttir 2014). Source: Table by authors.

3.2.2. Emerging Wind Power Systems: Floating Wind Turbines

Floating wind turbine structures (Figure 4) are advanced systems designed to capture wind power in deeper waters where traditional fixed-bottom turbines are not feasible. The concept of floating turbine structures originated in the 1970s and 1980s, as engineers sought solutions to overcome the challenges posed by water depths greater than 50 m, where the seabed is too deep for fixed structures. Although floating turbines emerged as a promising solution for these deep-water locations, substantial investment and development did not begin until the 2000s. The first significant prototype, the Hywind project, was developed by Statoil (now Equinor) off the coast of Norway in 2009. This floating platform successfully supported a wind turbine in deep waters, marking a major milestone. Following this success, numerous pilot projects were launched globally, leading to the development of various floating wind turbine designs, such as spar buoys, semi-submersibles, and tension-leg platforms.

Several countries have made substantial strides in floating wind systems, demonstrating their potential for large-scale renewable energy production and broader commercial deployment. In Norway, the Hywind Tampen, a floating offshore wind farm located in the North Sea approximately 140 km off the coast, is anchored to the ocean floor at a depth of 260–300 m. Hywind Tampen is the world's first renewable energy power source for offshore oil and gas, and when commissioned in November 2022, it was the world's largest floating offshore wind farm. In Portugal, WindFloat Atlantic, an offshore floating wind farm located 20 km off the coast of Viana do Castelo at a water depth of over 40 m, was the world's first semi-submersible floating wind farm and the first floating wind farm in continental Europe when commissioned in January 2020. In the UK, the Kincardine Offshore Wind Farm, located off the east coast of Scotland about 15 km southeast of Aberdeen, is installed on a semi-submersible foundation in water depths of 60 to 80 m. When commissioned in October 2021, it was the world's largest floating wind farm.

3.2.3. Challenges in Wind Power Generation

Wind power has a lower environmental impact than fossil fuel-based electricity generation (Dunnett et al. 2022). Wind turbines produce minimal life-cycle GHG emissions and do not contribute to air pollution (Bhandari et al. 2020). However, several challenges persist (Table 2), including intermittent wind patterns affecting power reliability, potential environmental impacts on wildlife and ecosystems, and the need for efficient energy storage solutions to balance fluctuations in wind energy production.

Intermittency is a primary challenge in wind power generation. Unlike traditional power sources with stable fuel inputs, wind energy depends on wind, which varies across geographic locations and time scales. Factors such as seasonal shifts, daily weather changes, and even minute-to-minute variations influence wind speeds, making energy output unpredictable. Coastal areas generally experience steadier winds due to land–sea temperature differences, whereas inland regions often face greater variability. This inconsistency complicates reliance on wind energy for a stable year-round power supply, even in wind-rich locations. For example, Texas, the leading US state in wind power generation, experiences higher wind speeds in winter. However, during summer, when electricity demand peaks due to air conditioning use, wind speeds typically decline. This mismatch between peak demand and wind availability necessitates backup power sources, such as natural gas, to compensate for shortfalls.

The need for a large surface area and spacing requirements means that wind farms typically require more land than other power stations. Even though the land between the turbines and roads can still be utilized for agriculture, the infrastructure, including turbines, access roads, transmission lines, and substations, typically results in "energy sprawl." Opposition to wind farms often arises from concerns about spoiling scenic areas and heritage sites (Reusswig et al. 2016). Habitat fragmentation and loss pose the greatest potential impacts on wildlife from onshore wind farms, but at the global scale, the ecological impact is minimal (Kuvlesky et al. 2007; Dunnett et al. 2022). Wind turbine blades contribute to fatalities among birds and bats, but the impact is notably lower when compared to other types of power stations. Specifically, wind farms are linked to around 0.3 to 0.4 fatalities per gigawatt-hour of electricity. However, this has a significantly lower impact when compared to fossil-fueled power stations, which record approximately 5.2 fatalities per gigawatt-hour (Sovacool 2009). Wind turbine blades are largely made of composite materials, often including fiberglass. While these materials are durable and lightweight, recycling them poses some challenges. The composite materials used in the blades are not easily recyclable through traditional methods. As a result, decommissioned blades have often been sent to landfills, raising concerns about their environmental impact (Liu and Barlow 2016). Environmental noise from industrial wind turbines is also a public health concern, of which sleep disruption is a major factor. For example, people residing within 1.4 km of industrial wind turbines experience poorer sleep, increased daytime sleepiness, and more significant mental health challenges compared to those living further than 1.4 km away (Nissenbaum et al. 2012).

Several types of energy storage solutions are used to manage fluctuations in wind energy, each with specific advantages and challenges. For example, the Hornsdale Power Reserve in South Australia, which utilizes Tesla's lithium-ion batteries (Figure 6), enhances grid stability by efficiently storing excess energy during high wind generation and quickly releasing it when wind speeds drop. Its key advantages include rapid response time and scalability, but challenges such as high battery costs, limited lifespan, and environmental concerns related to lithium mining remain (Boretti 2019). Dinorwig Power Station in Wales, UK, mitigates fluctuations by leveraging pumped hydro storage, rapidly generating electricity when wind energy supply decreases. This method offers high efficiency and long-term storage capacity, yet it requires significant infrastructure investment and is limited by geographical constraints, as suitable sites for pumped hydro are rare. Similarly, the McIntosh compressed air energy storage facility in Alabama supports renewable energy reliability by compressing and storing air in underground caverns, which is later released to drive turbines during periods of low wind generation. While this system provides large-scale storage with relatively low operational costs, it faces efficiency losses during energy conversion and is dependent on specific geological formations for underground storage.

3.2.4. System Modernization and Upcoming Breakthroughs

Key challenges in wind power generation are being addressed through focused innovations and high-tech solutions, including the following: (1) optimizing turbine efficiency with advanced blade designs and materials, (2) developing energy storage solutions to tackle intermittency, and (3) enhancing grid integration for a more reliable and sustainable energy infrastructure (Table 2). High-tech solutions are driving turbine growth, particularly in tip height, swept area, and maximum output. For instance, commercially available turbines saw tip heights increase from just over 100 m in 2010 (3 MW turbines) to more than 200 m in 2016 (8 MW turbines), with a 230% rise in swept area. Larger swept areas allow turbines to capture more wind, boosting energy production. Looking ahead, the industry aims for 12 MW turbines reaching 260 m, approximately 80% of the height of the Eiffel Tower, while planning for 15 to 20 MW turbines by 2030. Larger turbines, however, require bigger foundations, which drive up capital costs. Nonetheless, these turbines offer reduced operational and maintenance costs, ultimately lowering electricity production costs (IEA 2019).

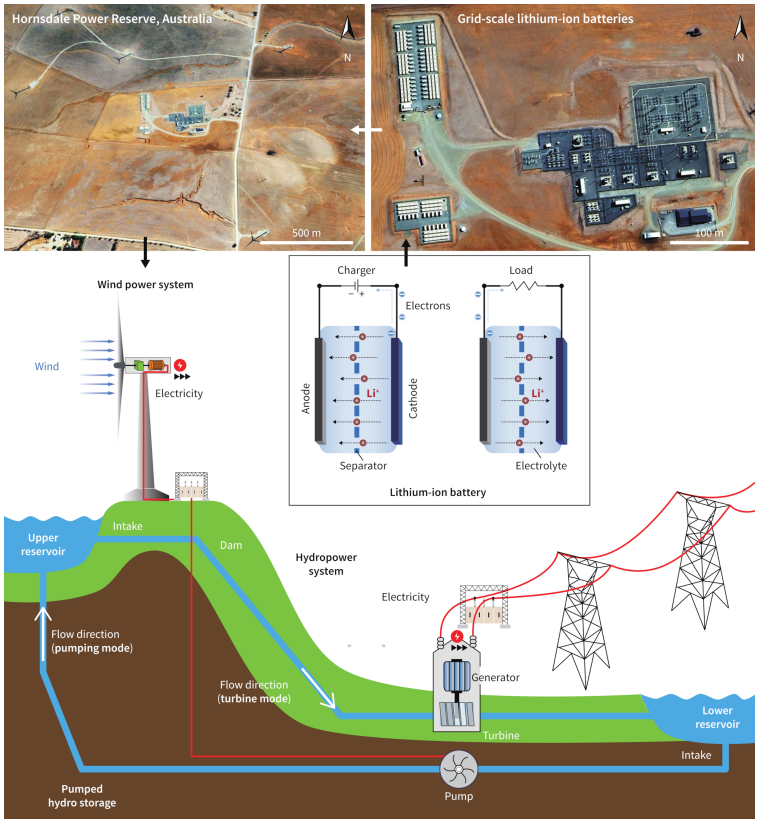


Figure 6. Schematic diagrams and photos illustrating the integration of energy storage systems (e.g., pumped hydro storage and lithium-ion batteries) with wind system (pumping mode) and hydropower system (turbine mode). Source: Figure by authors.

4. Hydropower

4.1. Strategic Role of Hydropower in Navigating Energy Transition Challenges

Hydropower, also known as hydroelectric power, has a rich history originating from ancient waterwheels and the Industrial Revolution, serving as a source of mechanical power (Breeze 2018). The establishment of the first hydroelectric power plant in 1882 marked a transformative shift towards electricity generation, and large-scale dam projects such as the Hoover Dam played a defining role in shaping hydropower development throughout the 20th century (Allerhand 2020; Kwak et al. 2014). Today, hydropower plays a crucial role in the transition to clean energy, not

only through the massive quantities of low-carbon electricity it produces but also through its unmatched capabilities for providing flexibility and storage (Bartle 2002; Rex et al. 2014; Killingtveit 2019).

Many countries have abundant water resources in the form of rivers and lakes, while others achieve similar objectives by building reservoirs (Rex et al. 2014; Kaygusuz 2004). Ethiopia, for example, is gifted with an extensive network of rivers (Degefu et al. 2015), while Bhutan boasts a mountainous terrain with sufficient water bodies (Dhakal 1990). Hydropower infrastructure makes a substantial contribution to economic growth, impacting not only developed nations but also developing ones (Yüksel 2007; Balat 2006). Ethiopia has invested in hydropower through projects like the Grand Ethiopian Renaissance Dam, creating jobs, fostering local skills, and significantly stimulating economic development, largely driven by a renewable energy source (Abtew and Dessu 2019). Similarly, hydropower initiatives in Bhutan have played a pivotal role in enhancing the economic landscape, being fully driven by a renewable energy source (Dhakal 1990).

Hydropower is consistent with the principles of environmental sustainability, and both developed and developing nations recognize the vital role of clean energy in mitigating climate change and reducing GHG emissions (Yüksel 2007; Balat 2006). Indeed, nations investing in hydropower enjoy increased access to international support and funding for renewable energy projects. This is attributed to the alignment of hydropower potential with areas where electricity demand is most critical, such as in many developing countries, thereby establishing hydropower production as the least-cost method of supplying electricity (Rex et al. 2014).

4.2. Strategic Role of Hydropower for Balancing Intermittent Renewable Energy Sources

Hydropower emerges as a versatile and essential component within the clean energy infrastructure, with its influence reaching far beyond electricity generation (Pandey et al. 2021; Killingtveit 2019; Dujardin et al. 2017). Firstly, hydropower plays a crucial role in frequency regulation, a critical service for maintaining the optimal functioning of the power grid. The frequency of electrical power must be consistently upheld for the grid to operate optimally. Hydropower facilities excel in this aspect by rapidly adjusting their output. By modulating the flow of water through turbines, hydropower plants can speedily respond to changes in demand, ensuring that the frequency of electricity within the grid remains within the required range. This dynamic regulation is essential for preventing disruptions and maintaining the consistency of the power system (Killingtveit 2019; Xu et al. 2018). Secondly, it provides voltage support, a valuable service that helps maintain stable voltage

levels, ensuring the reliability of the power grid and the optimal performance of electrical devices. Hydropower plants are equipped to respond promptly to changes in voltage, providing the necessary support to keep the voltage within specified limits. This capability enhances the resilience of the power system, safeguarding against voltage-related issues (Key et al. 2013). Thirdly, it plays an important role in contingency reserves, a service that acts as a safety net, ready to compensate for sudden changes in electricity demand or unforeseen failures in other parts of the grid, contributing significantly to the stability and reliability of the power grid. Hydropower facilities, with their ability to adjust output rapidly, serve as reliable sources for these contingency reserves. In times of unexpected events or fluctuations, hydropower contributes significantly to the stability and reliability of the power grid (González-Inostroza et al. 2021). Fourthly, it provides load following, a valuable service that ensures a dynamic balance between electricity generation and consumption, contributing to overall grid stability. This capability is particularly significant in today's energy landscape, where renewable sources like solar and wind exhibit variability (Yu et al. 2019). Fifthly, it provides a black-start service, which is vital in swiftly restarting the power system in the event of a complete outage, ensuring a prompt restoration of electricity to the grid. Hydropower plants, with their capability to initiate electricity generation swiftly, are well suited for this black-start service (Gracia et al. 2019). Lastly, hydropower plays a significant role in grid-scale energy storage, a service that involves storing excess energy during periods of high generation and releasing it when demand is high or renewable sources are not producing. As intermittent renewables such as wind and solar power become more prevalent, the need for efficient energy storage becomes essential. The utilization of hydropower in this balancing act is fundamental for upholding grid stability and optimizing the seamless integration of intermittent renewables into the broader energy mix. This, in turn, aids in maintaining grid stability and optimizing the integration of intermittent renewables into the broader energy mix (Killingtveit 2019; Castillo and Gayme 2014).

4.3. Hydropower Systems and Priorities for Modernization

Hydropower systems (turbine mode in Figure 6 and Table 3) employ the energy of flowing or falling water to generate electricity (Balat 2006). These systems typically involve the construction of dams, reservoirs, and generators to capture and utilize the energy inherent in water movements (Killingtveit 2019). Large-scale hydropower systems (e.g., the Three Gorges in China) often involve substantial infrastructure, including large dams and reservoirs (Jiang et al. 2018). On the other hand, small-scale hydropower systems are more decentralized, making them well

suited for supplying power to local communities and industries (Killingtveit 2019). Hydroelectric generation involves diverse forms such as conventional hydropower, run-of-river, pumped storage, tidal, wave, and offshore. Each form possesses distinct advantages and applications, offering a versatile range of options for clean and renewable energy generation (Flatley 2023; Wilberforce et al. 2023).

The global pursuit of sustainable and accessible energy sources has led numerous countries to prioritize hydropower as a primary choice (Yüksel 2007; Kaygusuz 2004). In the aftermath of the 1973 oil crisis, hydropower established itself as a clean energy source ahead of solar and wind (Schumacher 1985). Hydropower represented approximately 19.8% in 2010 and 16.9% in 2020 of the total worldwide electricity generation (Figure 7), demonstrating its early prominence in the energy transition (Killingtveit 2019; Rex et al. 2014; Bartle 2002). Currently, eight countries have achieved full economic dependence on clean energy, with hydropower contributing from 70.4% to 100% of national electricity generation (Figure 7b). However, hydropower constitutes a comparatively smaller proportion of renewable power generation in industrial powerhouses, ranging from 59.5% to 4.2% (Figure 7b). In addition, solar energy was projected to effectively surpass hydropower in 2024, becoming the second significant clean energy source with approximately 15.2% of the total worldwide electricity generation. By 2027, it is projected to hold the third position after both solar and wind, contributing to 14.1% of the total worldwide electricity generation (Figure 2b). Despite this decline in comparison to solar and wind power, hydropower is projected to experience a substantial surge, potentially doubling or surpassing its current annual share value by 2050 (Killingtveit 2019).

Components of hydropower systems receiving more attention in system development include dams, turbines, generators, and transmission lines (Figure 6 and Table 3). Modernization efforts focus on optimizing hydroelectricity generation and enhancing sustainability in large-scale projects (Jiang et al. 2018; Moran et al. 2018). Additionally, the exploration of new hydropower energy sources is prioritized for further growth within the clean energy sector (Zheng et al. 2015). For instance, research is being conducted to harness the electric potential of rain, utilizing energy from raindrop impacts. Although this concept is still in its early stages, emerging technologies are being tested and prototyped for rain power. One innovative approach includes the use of hybrid solar panels, called "all-weather solar panels," which can generate electricity from both sunlight and rain (Tang et al. 2016).

Table 3. Characteristics of hydropower systems.

Layout			Operational Dynamics			Upcoming Breakthroughs		References
Name	Description	Components	Capacity	Applications	Challenges	Technical	Sustainability	
Water source	Natural (rivers and lakes) and artificial (reservoirs and canals) water bodies	Dams regulating flow; turbines converting kinetic energy to electricity	High in regions with significant rainfall, snowmelt, large river systems, and mountainous terrain	Local power and national grids	Altered ecosystems and seasonal variability	Efficiency and storage enhancements	Ecosystem conservation	He et al. (2024), Wang et al. (2022b), Lu et al. (2020), and Johnsen et al. (2011)
Dam	Gravity, arch, and buttress dams for water control and storage	Advanced materials and spillways for regulation	<10 MW–22,500 GW	Hydropower, irrigation, and water supply	Ecosystem disruption and sedimentation	Safety and material excellence	Eco-friendly systems	Angelakis et al. (2024), Schmitt and Rosa (2024), Shang et al. (2022), Wasti et al. (2022), and Di Baldassarre et al. (2021)
Turbine	Pelton (high head), Francis (medium head), and Kaplan (low head)	Impulse, reaction, and axial flow turbines	<100 kW–>50 MW	Energy conversion based on water flow conditions	Mechanical wear and aquatic impact	Higher efficiency and durable materials	Eco-friendly systems	Kabeyi and Olanrewaju (2025), Karre et al. (2022), Khan et al. (2021), Elbatran et al. (2015), and Dorji and Ghomashchi (2014)
Generator	Synchronous (constant speed) and asynchronous (variable speed)	Rotating magnetic fields and electromagnetic induction	<100 kW–>1000 MW	Large-scale (synchronous) and small-to-medium-scale (asynchronous)	Synchronization issues and efficiency limitations	Efficiency, maintenance, and smart grid integration	Recyclable materials	Singh and Gao (2022), Verma et al. (2025), Xiong et al. (2022), and Mohale and Chelliah (2021)
Transmission lines	Overhead (on towers) and underground (buried cables)	Conductors (overhead) and insulated cables (underground)	<33–>765 kV	Long-distance (overhead), urban, and sensitive areas (underground)	Visual and weather impacts (overhead) and high cost (underground)	Transmission losses and smart grid integration	Eco-friendly transmission systems	Ushakov et al. (2023), Nguyen et al. (2021), Tuinema et al. (2015), Doukas et al. (2011), Umeda et al. (2007), Söderman (2006), and Furby et al. (1988)

Lower values of estimated capacity correspond to small-scale applications, while higher values correspond to large-scale applications, except for water sources. Source: Tabe by authors.

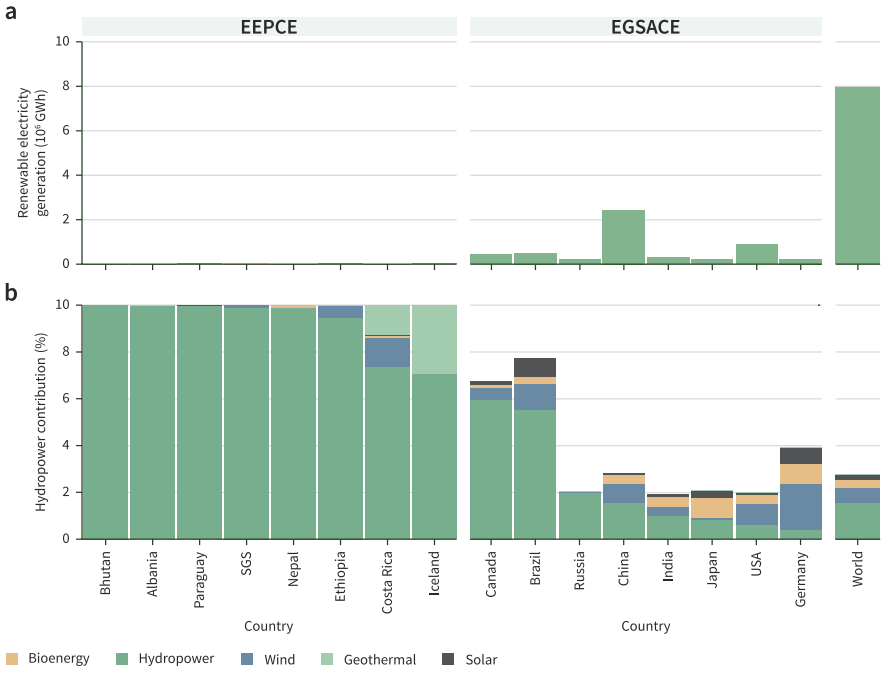


Figure 7. Global economic reliance on clean energy shown by (**a**) renewable electricity generation and (**b**) the contribution of hydropower. Source: Authors' compilation based on data from Ember (2023).

5. Energy Storage Systems

Energy storage systems (Figure 6 and Table 4) play a prominent role in the renewable energy revolution and serve as a crucial tool for mitigating climate change (Few et al. 2016). Energy storage systems involve a variety of technologies designed to capture, store, and manage energy for later use (Table 4). These technologies play a crucial role in the integration of renewable energy sources into the broader energy grid (Chen et al. 2009).

Table 4. Characteristics of energy storage systems.

Layout			Operational dynamics			Upcoming Breakthroughs		References
Name	Description	Components	Capacity	Applications	Challenges	Technical	Sustainability	
Battery storage	Stores electricity for later use	Lithium-ion, lead–acid, flow, solid-state, and sodium-ion	3 kWh–250 MWh	Grid stability, electric vehicles, residential storage	Resource scarcity, environmental impact, and safety risks	Energy density and lifespan	Eco-friendly materials and recycling	Shi et al. (2024), Simpa et al. (2024), Grgur (2023), Rouholamini et al. (2022), Mrozik et al. (2021), and Koehler (2019)
Pumped hydro storage	Pumps water uphill for later electricity generation	Open-loop, closed-loop, and variable-speed	<10–3600 MW	Grid balancing and peak load management	High costs, site limitations, and energy losses	Turbines and efficiency optimization	Eco-friendly systems	Nikolaos et al. (2023), Das et al. (2021), Kong et al. (2017), Pérez-Díaz et al. (2015), Yang and Jackson (2011), and Deane et al. (2010)
Compressed air storage	Stores compressed air underground for later electricity generation	Adiabatic and isothermal	10–1000 MW	Grid support and peaker plant replacement	Site constraints, energy loss, and high costs	Efficient compression/expansion tech	Emission-free systems	Li et al. (2023), Bazdar et al. (2022), Wang et al. (2017), Lund and Salgi (2009), and Denholm and Kulcinski (2004)
Thermal energy storage	Stores heat for later electricity generation	Sensible, latent, thermochemical, and cryogenic	<10–5907 MWh	Solar plants, district heating, and industrial use	Heat loss, material limits, and high costs	Materials and insulation	Integration into renewables and lifecycle	DEWA (2025), Sadeghi (2022), Cabeza (2021), Li and Zheng (2016), and Habeebullah (2007)
Flywheel storage	Stores kinetic energy in a rotating mass	Magnetic bearings and vacuum enclosures	~100 kW–100 MW	Grid regulation, backup power, and transit systems	High costs, wear, and limited duration	Efficiency and lifespan	Eco-friendly materials and disposal	Pullen (2022), Choudhury (2021), Pareis and Hittinger (2021), Tang et al. (2012), and Bornemann and Sander (1997)

Table 4. *Cont.*

Layout			Operational dynamics			Upcoming Breakthroughs		References
Name	Description	Components	Capacity	Applications	Challenges	Technical	Sustainability	
Hydrogen storage	Stores hydrogen for fuel cell electricity generation	Compressed/liquid hydrogen and metal hydrides	~330 kWh–150 GWh	Fuel cells, industry, and transport	Low density, leakage, and high costs	Enhanced storage and efficient production	Green hydrogen and infrastructure adaptation	Jayachandran et al. (2024), Ma et al. (2024), Wang et al. (2023), Preuster et al. (2017), and James et al. (2016)
Supercapacitors	Fast-charging energy storage	Double-layer and pseudocapacitors	~2.3–1000 V	Electric vehicles, grid stability, and electronics	Low energy density and self-discharge	Higher capacity and longer cycle life	Eco-friendly materials	Muzaffar et al. (2024), Huang et al. (2019), Sharma et al. (2019), and Li et al. (2017)
Molten salt storage	Stores heat in molten salt for later electricity generation	Solar salt and two-tank system	~10–1200 MWh	Solar power, district heating, and industry	Corrosion, high costs, and energy losses	Efficiency and materials	Lifespan	Roper et al. (2022), Bauer et al. (2021), Peiró et al. (2018), Relloso and Gutiérrez (2017) and Angelini et al. (2014)

Lower values of estimated capacity correspond to small-scale applications, while higher values correspond to large-scale applications. Source: Table by authors.

Battery storage, particularly lithium-ion batteries (Figure 6), has played a crucial role in enhancing the storage capabilities of solar energy (Armand et al. 2020). Innovations and high-tech solutions in batteries are expected to bring about improvements in energy density, cycle life, and cost-effectiveness, thereby enhancing the accessibility and efficiency of energy storage systems (Grey and Hall 2020). The integration of solar energy storage with smart grid technologies is poised to revolutionize energy distribution, enabling more efficient responses to demand fluctuations and contributing to overall grid stability (Armand et al. 2020; Grey and Hall 2020). Advancements in flow batteries and capacitors and the exploration of novel materials for thermal storage are expected to play a pivotal role in shaping the trajectory of solar energy storage (Zhao and Burke 2021; Esan et al. 2020). This, in turn, will contribute to a global increase in energy access while reducing reliance on coal, a current predominant source of waste and emissions causing climate change (Few et al. 2016).

6. Renewable Energy, Innovation, and High-Tech as Pillars of a Climate Resilience

Renewable energy is indispensable for driving transformative change in both mitigating climate change and promoting sustainable development (Figures 1–7 and Tables 1–4). On the one hand, it plays a critical role in reducing GHG emissions and displacing fossil fuels, thereby helping to limit global warming. On the other hand, it supports adaptation by enhancing resilience to climate impacts through decentralized and sustainable energy solutions. This dual contribution makes renewable energy, innovation, and high-tech foundational elements in the global pursuit of climate resilience (IEA 2022a; Xie et al. 2021; den Elzen et al. 2013).

6.1. Climate Change Mitigation

Mitigation efforts aimed at preventing GHG emissions are heavily reliant on transitioning away from fossil fuels and establishing carbon-neutral energy systems (Anderson and Rezaie 2019; Killingtveit 2019; Abraham 2017; Mulder et al. 2017; Weaver et al. 2017; Kannan and Vakeesan 2016; Archer and Jacobson 2005). Among renewables, solar and wind have emerged as the fastest-growing sources of electricity globally (Figure 2b), demonstrating their potential to significantly displace fossil fuels. This is supported by the IEA (2022a), which revealed that the rapid expansion of solar PV and wind generation has prevented approximately 465 Mt of CO_2 emissions in the power sector. Clean energy technologies, such as electric vehicles and heat pumps, have prevented an additional 85 Mt of CO_2 emissions, further

underscoring the critical role of renewable energy and high-tech solutions in climate change mitigation.

However, the intermittent nature of renewable energy sources, such as solar and wind, poses a challenge to their widespread adoption. This issue has been effectively addressed through advancements in energy storage systems (Figure 6 and Table 4). Boretti (2019) emphasized that these innovations are particularly crucial in regions vulnerable to the impacts of climate change, such as arid and semi-arid areas. A notable example is the Hornsdale Power Reserve in South Australia, the world's largest lithium-ion battery (Figure 6), which has played a key role in stabilizing the grid and reducing reliance on fossil fuel-based peaking plants.

Looking ahead, high-tech solutions show significant promise in addressing emissions in hard-to-abate sectors, such as heavy industry and long-haul transportation. Jayachandran et al. (2024), Ma et al. (2024), Wang et al. (2023), Preuster et al. (2017), and James et al. (2016) argue that green hydrogen, produced through electrolysis using renewable electricity, could revolutionize these sectors by providing a zero-emission alternative to fossil fuels.

6.2. Climate Change Adaptation

Adaptation to climate change, particularly in response to shifting precipitation patterns, rising sea levels, and climate extremes, is closely tied to reducing reliance on fossil fuels (Wang et al. 2022a; Ali and Mujeeb-Kazi 2021; Seneviratne et al. 2021; Tollefson 2018; van Kooten 2018; Stern and Kaufmann 2014; Princiotta 2009; Tomczak 2005). Solar energy potentials, which are relatively high in every region (Figure 2a), along with the successful use of small-scale wind turbines in Shenzhen, China (Figure 4), demonstrate that solar PV and other decentralized renewable energy systems play a transformative role in climate adaptation strategies. These observations align with those of Amin et al. (2021), who highlight that in climate-vulnerable regions, decentralized renewable energy systems provide reliable energy access. For instance, solar home systems have been extensively deployed in flood-prone rural regions of Bangladesh, ensuring uninterrupted electricity during extreme weather events. This reliability stems from renewable energy infrastructure being more resistant to disasters compared to fossil fuel-based systems, thereby strengthening disaster resilience and supporting long-term climate adaptation efforts. Similarly, Nikolaos et al. (2023), Das et al. (2021), Kong et al. (2017), Pérez-Díaz et al. (2015), Yang and Jackson (2011), and Deane et al. (2010) emphasize the critical role of hydropower and pumped hydro storage systems in water management, further underscoring the importance of the energy–water nexus

in climate adaptation. Beyond their climate-resilience benefits, renewable energy and high-tech solutions also contribute to global stability by reducing conflicts driven by fossil fuel dependence. Yergin (1991) and Butti and Perlin (1981) argue that renewable energy and high-tech solutions mitigate the geopolitical tensions resulting from catastrophic damage (e.g., oil spills and nuclear accidents) and armed conflicts over finite resource control.

6.3. Climate Neutrality

Achieving climate neutrality requires the widespread adoption of renewable energy, carbon removal strategies, and zero-emission solutions (IEA 2022a). The near-complete reliance on wind power and hydropower in certain small economies across all continents (Figures 5 and 7), along with the rapid growth of solar PV and wind power generation in major economies (Figure 2c,d), indicates a global shift toward renewable energy and the critical role of high-tech solutions in developing climate-resilient energy systems. These findings align with the observations of Balal and Giesselmann (2024), Ghodusinejad et al. (2022), Goldin et al. (2014), Maddilety et al. (2024), and Yap et al. (2022), which suggest that renewable energy and high-tech solutions are driving key zero-emission innovations, such as electric vehicles. The IEA (2022a) reinforces these observations, reporting a surge in the global adoption of electric vehicles in 2022, with sales surpassing 10 million units (over 14% of total car sales). Similarly, Jayachandran et al. (2024), Ma et al. (2024), Wang et al. (2023), Preuster et al. (2017), and James et al. (2016) emphasize the importance of green hydrogen production as a zero-emission solution for hard-to-abate sectors such as heavy industry and long-haul transportation. Specifically, Morimoto et al. (2023) highlight the critical role of renewable energy and high-tech solutions in carbon removal technologies, which achieve 47% for methanol, 99% for methane, 545% for gasoline, and 621% for diesel.

6.4. Low-Carbon Economy

The global shift toward a low-carbon economy remains a substantial challenge (IEA 2022a). The relatively low proportion of renewable electricity generation in India (19.0%), the USA (20.2%), Russia (20.4%), Japan (21.0%), China (28.1%), and Germany (39.1%) compared to other nations (Figure 7) indicates the difficulties of reducing carbon dependence. This slow progress aligns with the findings of the IEA (2022a), showing only a 1.7% global reduction in industrial emissions (9.2 Gt), largely driven by a 161 Mt CO_2 decrease in China's industry emissions (i.e., 10% decline in cement production and 2% decline in steel making). However, transitioning to a

low-carbon economy presents substantial socio-economic benefits, particularly in job creation. Renewable energy, especially wind power, generates two to five times more jobs than the fossil fuel industry. For example, employment in the wind energy sector alone grew from 0.63 million in 2010 to 1.254 million in 2020, excluding indirect jobs. Notably, these jobs offer better wages compared to other sectors within the electric power industry (Haidi and Cheddadi 2022).

6.5. Zero-Emission Technologies

Zero-emission technologies are crucial for reducing the global reliance on fossil fuels, which are the major source of CO_2 emissions (IEA 2022a). Various renewable energy generation and storage systems examined in this study (Figures 2–7 and Tables 1–4) operate without emitting GHGs. These findings align with the IEA (2022a) regarding industrial emission reductions and achieving near-zero carbon footprints through the adoption of cutting-edge technologies, such as energy-efficient manufacturing processes and electric vehicles. In line with this, Lyu et al. (2024) and Wang et al. (2021) highlight that integrating renewable energy into battery electric vehicles significantly reduces emissions compared to gasoline-powered alternatives, with CO_2 reductions ranging from 8.72 to 85.71 kg per vehicle per month. Moreover, advanced battery electric vehicles, which incorporate high-efficiency systems and the latest technological innovations, offer even greater environmental benefits, including a 30% reduction in NO_2 and $PM_{2.5}$ emissions.

7. Conclusions

7.1. Key Findings

Addressing climate change requires the adoption of innovation and technology. Since the 1973 oil crisis, the environmental impact of fossil fuels has driven a shift toward renewable energy. In recent years, the increasing severity of climate change consequences has further emphasized the urgent need to build a more resilient energy infrastructure. Key innovations for building a climate-resilient world include cleaner energy sources such as solar, wind, and hydropower, as well as energy-efficient systems designed to manage the intermittency of renewable energy and store surplus energy. These innovations ensure not only a steady energy supply but also effectively reduce GHG emissions and mitigate the impacts of climate change. Solar power efficiency has been enhanced through PV cells and CSP, wind energy with improved turbine designs, and hydropower through designs that support larger dams. Energy storage systems have been enhanced through various high-tech solutions, including

battery storage, pumped hydro storage, compressed air storage, thermal energy storage, flywheel storage, hydrogen storage, supercapacitors, and molten salt storage.

7.2. Practical Implications

Transitioning to renewable energy is critical for addressing climate change. This global shift requires the large-scale deployment of solar PV, CSP, wind, and hydropower systems to achieve climate neutrality. The successful integration of intermittent renewable sources demands particular attention to energy storage. High-tech solutions, particularly those designed to manage supply–demand dynamics across the electrical grid, are essential for the reliable integration of renewable energy. Renovating existing infrastructure, particularly energy grids, is crucial for accommodating these renewable sources and ensuring a stable, resilient energy system.

7.3. Recommendations

Ensuring global access to clean energy and building a climate-resilient world calls for further research into renewable energy sources and energy storage systems. Advances in these areas drive innovation and high-tech solutions, paving the way for scalable systems that contribute to climate neutrality and zero-emission technologies. Notably, the scalability of energy systems not only reduces dependence on single energy sources but also promotes a more stable and resilient global energy infrastructure.

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Conflicts of Interest: The authors declare no conflicts of interest.

Acronyms

CEE	Central and Eastern Europe
CIS	Commonwealth of Independent States
CPA	Centrally Planned Asia
CSP	Concentrated solar power
EEPCE	Eight economies exclusively powered by clean energy

EGSACE	Economies generating substantial amounts of clean energy
FSU	Former Soviet Union
GHG	Greenhouse gas
KSA	Kingdom of Saudi Arabia
LAC	Latin America (South and Central America)
ME	Middle East
MENA	Middle East and North Africa
NA	North America
NA	Northern America
OECD	Organization for Economic Co-operation and Development (Pacific Region)
OSPS	Ouarzazate Solar Power Station
PA	Pacific Asia
PTSC	Parabolic Trough Solar Collector
PV	Photovoltaic
SA	South Asia
SGS	South Georgia and the South Sandwich Islands
SSA	Sub-Saharan Africa
STP	Solar tower power
TES	Thermal energy systems
UAE	United Arab Emirates
UK	United Kingdom
UNDP	United Nations Development Programme
USA	United States of America
WE	Western Europe

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Climate Policy Reform Through the Indigenous Lens of the Institutional Analysis and Development Framework: A Case of the Bangladeshi Santals

Parimal Kumar Roy

1. Introduction

Geographically, Bangladesh is a South Asian and the seventh most climate-vulnerable country in the world, with 170 million people (Hossain 2023). Despite a robust academic debate on numbers and name issues, the government's Small Ethnic Group Cultural Organisation Act 2010 (hereinafter Act 2010 as the mother of legal provision) in Bangladesh names fifty ethnic groups that are considered as such instead of Indigenous, but here, the term Indigenous will be used. Since Indigenous people are in the minority in terms of numbers, they are always overlooked, either through intervention or policy exclusion. In this chapter, the author reviewed the existing policy, act, and government documents to propose an Indigenous Community Perspective (ICP) model to reduce calamities in the community and further intend to analyse the development framework to understand the institutional drivers and constraints of climate policy reforms for the Santals. The Santals is one of the Indigenous groups living in northern Bangladesh. According to recent ethnographic studies of the Santals in Bangladesh (Roy 2024; Besra 2014; Jahan 2020), it is assumed that the community historically migrated to and settled in Bangladesh.

Climate change is a global phenomenon that affects many aspects of society, such as natural resources, health, education, and the economy (Eckstein et al. 2021). To mitigate its susceptibility, researchers focused on these issues give priority to Indigenous Knowledge Systems (Datta et al. 2024; Cajete 2020; Roy et al. 2024) and believe that "the solutions are to be sought on the same levels of complexity with joint production of knowledge involving communities" (Islam and Shafie 2017). The scope of this chapter is the Indigenous communities of Bangladesh—like the Santals—and how to address the challenge of climate change and coordinate responses in the community. In this context, the Indigenous Community Perspective (ICP) is presented here as a sustainable solution to understand the vulnerability of the Santals community as well as others.

To understand the substantial impacts of climate change on ethnic communities, we need to contemplate the historical perspective of institutional change and policy reform interventions that have occurred in Bangladesh (Datta et al. 2024). This study contributed to understanding modifications, and the author conducted in-depth interviews and participatory observations with the community.

Against this backdrop, this research provides an understanding of how communities adapt to the changing climate and the challenges they face in this vicinity. The author also highlights the cultural and social factors that influence how communities respond to climate change and the implications of these responses in terms of their well-being.

The ICP's insights are valuable for empathising with the impacts of climate variation on Indigenous communities in Bangladesh and for shaping effective responses to these impacts. By working in close collaboration with communities and policymakers, the ICP can ensure that the types of needs and perspectives of affected communities are integrated into the design and implementation of climate policies. The ICP is one of these strategies used for mitigating the climate challenges of Indigenous communities in Bangladesh. To open up policy windows, political economics and the political forest, to make a political–ecology argument, namely that forests today have been produced through politics, bring research and policy closer to the requirements of vulnerable groups throughout the entire policy process (Giddens 2015; Vandergeest and Peluso 2015).

2. Materials and Methods

2.1. Study Area

Dinajpur is one of the oldest districts in Bangladesh. The Indian state of West Bengal borders it. This chapter originated from my PhD fieldwork and was completed in one of the villages under the Biragnaj subdistrict (Figure 1). Birganj Upazilla is located between the Dinajpur and Thakurgaon highways. It is a subdistrict with diverse people and cultures, 27 km from Dinajpur headquarters. This subdistrict consisting of 11 unions and 1 municipality. Its area is 413 square metres. Two rivers, Dhepa and Karatoa, flow through this upazila. People of different communities live there, including Hindus, Muslims, Christians, and the Santals community, even though this community is being converted to Christianity. Communal harmony exists among the people. Paddy, wheat, jute, potato, mustard, vegetables, and fruits are the main crops of this upazila. Apart from the rice mill and brick field, no other industrial factories exist. The communication system is better than in other parts

of the district as this upazila is connected to the highway, forging a link with the whole country.



Figure 1. Study area. Source: Author's compilation based on data from Bangladesh National Portal (n.d.).

2.2. Methods

The Santals, one of the nineteen Indigenous communities in northern Bangladesh, are the main focus of this research. The author initially reviewed the government's documents, such as policies and acts—enacted by a legislative body or parliament and laws—derived from parliament and strategies regarding people. Santals is discussed with contemporary concern and a deep nexus of field data. Participant observation and interviews were used to collect the data, which were analysed thematically. Data credibility was checked by prolonged engagement and peer debriefing. Further, data dependability was checked by using two 'workshops' (Chilisa 2019; Creswell and Creswell 2017) and coding–recoding tools to ensure the quality and trustworthiness of the data used in this research. However, the study area is dominated, indeed, by the most common cultures, i.e., Bengali people such as Hindu and Muslim. The village is now diversified, and a large portion of Santals work in agricultural sectors.

3. Results

3.1. Absence of Self-Determination to Raise the Climate Justice Voice

This study follows the Act 2010; according to this act, Bangladesh now has 50 small Indigenous groups. In a broad sense, there are 19 Indigenous groups in the plain land of Bangladesh, and the Santals is the largest group in the northern part, and the group lives in the greater Dinajpur and Rajshahi regions. Moreover, in this chapter, the author has used the term 'Indigenous groups' instead of ethnic groups. The Santals people used to live adjacent to a forest called the Singra Sal forest (Shorea robusta), but they are now far away and do not have the right to enact the government's rules, policies, and acts. They used to have the rights to collect fuel, wood, and fruits and used to go hunting and gathering as part of customary systems—known as L'Bir. The community people said that they are restricted in terms of cutting off the trees due to the gods living on the tree. This ethical matter led to protecting the forest and ensuring climate justice. Now the forest department is working to increase forest volume, but it is reducing day by day. The Santals people claim that they do not have the self-determination needed to raise their voice for nature protection.

3.2. Indigenous Communities Are Defenceless and Absent in Policy Frameworks

There are a good number of policies based on mitigation, adaptation, and support that address climate change in Bangladesh. But for Indigenous people, like the Santals, their participation was absent in the policy formulation process. During conversations with informants, it was said that during policy formulation, Indigenous people lacked participation. As a consequence, the Santals is not aware of climate change and is not involved with climate protection interventions. In terms of policies, Table 1 indicates a few related to the research community. The Santals is not aware of this and do not know the ways in which they are protected from susceptible circumstances.

Recognising the unique challenges that Indigenous groups such as the Santals faces in responding to climate change is essential. When creating and implementing climate change policies, the community's needs and viewpoints should be considered in adaptation and mitigation strategies. This can include recognising their rights to land and natural resources, such as forest management, supporting their traditional knowledge and practices, and providing appropriate and culturally sensitive adaptation support. The Santals community in Bangladesh is particularly vulnerable to the consequences of climate change, so to help them, tailored interventions to their

needs and sensitivity to their culture are indispensable. Otherwise, policy-based action would bring about negative results, such as the Kaptai dam for the Chittagong Hill Tracts Area or the Santals revolt in 2006 at Dinajpur against the coal mining project, which ended in bloodshed. For that reason, integrating the community's perspectives and requirements into the design and implementation frameworks of climate change policies and adaptation strategies is also critical, but it must be ensured that their implementation is effective and successful.

Table 1. National Policy Instruments (NPIs) in Bangladesh.

National Policy Instruments	Target Year	Climate Objectives	Sectoral Scope	Santals Community
National Sustainable Development Strategy-2010	2020	Adaptation and mitigation	Multisectoral	(Sarker et al. 2016; Barkat 2016; Hasan 2020; Jahan 2020; Besra 2014; Debnath 2010, 2012, 2020). All clarify and give the depiction that the Santals are being demotivated, impoverished, marginalised, and are incapable of meeting the policy's demand. Therefore, these failures promote thinking of new alternatives to face climate change to achieve the SDGs 2030 or Delta plan 2100.
National Adaptation Program of Action-2009 (revised)	onwards	Adaptation and mitigation	Multisectoral	
Country Investment Plan for Climate Change-2016	onwards	Adaptation and mitigation	Multisectoral	
National Determined Contributions-2017	2030	Adaptation and mitigation	Multisectoral	
National Environment Policy-1992	onwards	Supportive policy	Forest	
National Wetland Policy-1998	onwards	Supportive policy	Environment	
National Water Policy-1999	onwards	Supportive policy	Water	
National Biodiversity Strategy and Action Plan-2016 (revised)	onwards	Supportive policy	Biodiversity	
National Land Use Plan-2001	onwards	Supportive policy	Land use	
Delta Plan-2016	2100	Supportive policy	Multisectoral	
National Forest Policy-2015 (updated)	onwards	Supportive policy	Forest	

Source: Author's compilation based on data from Islam and Shafie (2017).

While visiting the Singra forest, the Sal trees (Shorea robusta) were cut off, the river, which is situated in the forest, was dry, and no water was found. But

this river was once the source of protein and income, via fishing, bathing, and swimming. The forest was also a source of herbal medicine for primary treatment in the community. It is unfortunate that the diverse policies and acts did not positively affect their livelihood.

3.3. Conflict Regarding Forest Use and Indigenous Livelihood

In the nation-state of Bangladesh, Indigenous communities have been deprived in the Chittagong Hill Tracts area since the 1960s, and more than 1,00,000 Indigenous dwellers were uprooted as a result of the implementation of the Kaptai Dam project (Adnan 2004; Chowdhury 2006). In independent Bangladesh, the conflict between the Bengali majority and Indigenous groups was prompted by military rulers in the 1980s by the arranged resettlement of the plainland Bengalis into hilly areas where Indigenous people have been living for thousands of years (Chowdhury et al. 2022; Roy et al. 2022). One day, the author visited the Santals' houses, and they were far away from the forest and showed grief, but the Muslim houses—one of the most common cultures—were very close to the forest. This indicates a trend: settler colonialism is also seen in the Singra Forest area. When the government declared the forest a restricted and reserved area, the Santals were kept far away from the forest, but Bengali people were moving very close to the forest, demonstrating settler colonialism (Veracini 2010; Wolfe 2006; Mamdani 2020), or viewing the forest as political, where the rights are reserved for the government to decide who will live or be accommodated there (Vandergeest and Peluso 2015). Many studies (Sumi and Bulan 2019; Debnath 2010; Jahan 2020; Besra 2014) have been conducted on land rights, empowerment, and education; however, legislation has allowed little room for Indigenous groups, particularly the Santals. Therefore, social scientists argue that Indigenous minorities are framing counterhegemony against the state of Bangladesh to protect their nature, Indigenous knowledge, and land rights, which the 1997 national accord lethally failed to imply (Ahmed 2010; Sarker et al. 2016; Uddin 2010; Van Schendel et al. 2000). There is no place in government policies or legislation for Indigenous people; as Mamdani said in 2020, "The birth of the modern state amid ethnic cleansing and overseas domination teaches us a different lesson about what political modernity is: less an engine of tolerance than of conquest" (Mamdani 2020).

Different sizes of eco-parks have been set up in Bangladesh, even though private amusement parks are also liable for the evacuation of Indigenous communities. From the East India Company (EIC) to Bangladesh, all governments have paid little attention to Indigenous communities regarding sustainable community development. The following Table 2 mentions notable acts, policies, and laws that have made

Indigenous groups—like the Santals—vulnerable and victimised by the development politics in Bangladesh. To reflect on our understanding, in Table 2, a few related acts and laws have been deliberated on regarding climate change issues.

Table 2. Period-wise policies, acts, and law upsetting Indigenous communities.

British Period (1757–1947)	Pakistan Period (1947–1971)	Bangladesh (1971–Today)
The Permanent Settlement Regulation-1793	The State Acquisition and Tenancy Act-1950	The Vested Property Act-1974
The Bengal Tenancy Act-1855	The Enemy Property Act-1965	The Acquisition of Immovable Property Act-1982
Forest Act-1927	Private forest ordinance-1959	The Acquisition of Immovable Property Act-1982
Assam Forest Regulation-1891		• The Krishi Khas jomi Bandobostha Nitimala-1995 • The Sarkari Jalmohal Babosthyapona Nity-2009 • Small Ethnic Groups Cultural Organisation Act-2010 • Biodiversity Act-2017 • Convention of Biodiversity-1992 but ratified 1994 in Bangladesh • Bangladesh Environment Conservation Act (BECA)-1998 • National Education Policy-2010 • Bangladesh Biodiversity Act-2015
		Revision of Social Forestry Rules-2004 (amendment, 2010)
		Protected Area Management-2017

Source: Author's compilation based on data from Roy et al. (2022).

Climate change is the most significant threat of the 21st century, and world leaders are anxious to establish climate justice (Eckstein et al. 2021). However, there are few studies on the impacts on or responses of these communities in Bangladesh (Chowdhury et al. 2022; Roy et al. 2023a, 2023b; Rahman 2023). At the same time, there is a wealth of information in the form of the local knowledge of Indigenous communities based on their observations, perceptions, and experiences over the years. As part of this PhD thesis, the author conducted 9 months of participant observation between 2022 and 2023 in the Santals' village, Dinajpur district, Bangladesh, to assess local perceptions and adaptations to climate change. The perceptions of the impacts of climate change were very detailed and provided numerous insights into local concerns. The data suggested that the region's local people have been experiencing

changes in climatic conditions and natural surroundings, including changes in their grazing pastures and agriculture; now, groundwater for irrigation is far out of reach, meaning that water must be collected from shallow areas or deep tube wells. Twenty years ago, farmers could access water just 50–70 feet away, but now it is more than 150 feet away; sunburn is more severe while working on agrifields now than it has been in the last 10 years for the Santals agri labourers. Not only the forest but also private trees are decreasing in number in place of brick fields. One brick field remains; over the last ten years, there have only been a few brick fields in the locality. Almost all houses are made of bricks, even the Santals' hamlet. It is well defined that the rules and acts were not enforced to stop environmental degradation, like the Biodiversity Act 2017; Revision of Social Forestry Rules 2004 (amendment, 2010); and the Bangladesh Environment Conservation Act 1998. On the other hand, according to Tables 1 and 2, few people are partially dependent on forests, rivers, and wetland-based activities, but the rules and acts have bound people to engage in alternative professions or livelihood works. This study suggests that Indigenous people have much to offer to the discourse on and actions countering climate change.

Like many others, the Indigenous minorities in Bangladesh are susceptible to the effects of climate change. Indigenous communities, either hilly or plain, depend on natural resources for their livelihoods, such as agriculture, forestry, and fishing. Now the changes in these resources due to climate change significantly influence their way of life. For example, changing rainfall patterns, increasing temperatures, and more frequent extreme weather events are affecting crop yields and causing food insecurity for the Santals community since they have little land.

Nevertheless, the law does not stand by them; however, the government came to them with a *'development gift'* (Mamdani 2020). This type of gift hurdles their life and ruins the customary law. Indeed, the Santals community's traditional knowledge and cultural practices are also threatened by climate change. For example, their traditional L' Bir system is being stopped to maintain the frequency and intensity of the Protected Area Management Rule 2017. The L'Bir system maintained the law and order of the community, but now it is extinct to them due to the enforcement of forest policies in Bangladesh.

3.4. Loopholes Amid Policy Linkage and Coordination

The GoB actively participates in international climate change discussions, such as the Paris Agreement, and some others are the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) 1992, and the Nagoya Protocol 2010, to name a few. The country also

collaborates with international organisations and development partners to access finance and technical assistance to support its climate change response. Therefore, there is an urgent need to address the challenges posed by climate change through an institutional policy to take a proactive approach to reducing environmental hurdles like heat waves and deforestation, riverbank erosion, and adapting to climate change's impacts on Indigenous groups' cultures. It is here that there is a significant loophole that the Indigenous groups' representatives are not considering in the policy formulation or implementation process at the community level that has been advised in the law, despite the fact that international and national documents like the CBD 1992, Nagoya Protocol 2010, Biodiversity Act 2017, and Act 2010 have provisions to include it. As part of international commitment, the country actively participates in international negotiations and works with development partners to access resources to achieve its climate change goals through the development framework of Bangladesh, which is shaped by its steps to manage the challenges posed at the local or national level. However, a pertinent question is as follows: how much do these types of linkages and coordination work to meet the drought, water level deepening, storm, unusual rain, and flood concerns, which are common natural hazards to the community? The answer from the field reflected in others' minds is that their voice could be more varied, and there is a big loophole in the development sectors in terms of linking and coordinating policy formulation or implementation.

3.5. Low-Carbon Demand but Decreased Forest Volume

The Singra Sal Forest (Shorea robusta) is one of the largest forests in Dinajpur; the Santals are now marginal in their socioeconomic condition, and they claim that the area of the forest is decreasing daily due to the versatile interventions of the government or most common people. When the Santals moved to the forest to hunt and gather or collect fuel wood, different policies and acts prohibited them from performing those activities; against this backdrop, the Santals questioned the researcher—what are the benefits of banning them from entering the forest? It was replied that it is a matter of the state, but the author stayed with the people and the forest and saw that there were permanent households and people, temporary shops, and people collecting fuel wood, all being carried out by people of the most popular cultures.

However, one key aspect of the development framework is the promotion of low-carbon and climate-resilient development through social forestation. It has been said that "the plant absorbs water from the soil through roots and releases it into the atmosphere during transpiration. This released water then forms clouds and

rains. Forestation can heal the environmental damage in Bangladesh. Forestation in Bangladesh can change the extreme climatic pattern" (Rahman 2023). Another critical aspect of development interventions is the integration of climate modification considerations into consequent planning and decision-making processes.

4. Discussion

Indigenous communities worldwide are particularly vulnerable and seek special attention from policymakers to determine their social identity, like self-determination. They have climate sensitivity because they often depend on natural resources for their livelihoods, such as agriculture, forestry, and fishing. Changes in these resources due to increasing populations put tremendous pressure on forests and change the scenario. State interventions like setting up coal mines and forest restrictions significantly control people's ways of life. In many cases, Indigenous communities closely relate to their environment and have traditional knowledge and practices that are well adapted to local customs and rituals. One respondent in the field stated, "The massive destruction of the forests of Bangladesh occurred during the last 40 years. Biodiversity has declined rapidly, and many species have disappeared. The forests are acutely impacted by over-exploitation, deforestation, excessive litter collection, encroachment, indiscriminate collection of economically important plant species (i.e., medicinal, fodder), and other forms of anthropogenic disturbances"; this statement reflects on the Singra Forest land.

Recognising Indigenous communities' unique challenges in responding to climate justice is significant. Their needs and perspectives must be considered in designing and implementing climate policies and adaptation strategies. Acknowledging their rights to land and natural resources is necessary to protect their customary knowledge and practices. Moreover, without the inclusion of their voice in the development framework, the development policy is errant in providing them with culturally appropriate and effective adaptation support. Hence, this study aimed to assess the vulnerability of the Santals to the impacts of climate change and the need for targeted and culturally appropriate support to address these challenges.

The country's Indigenous communities are the most disturbed, for example the Phulbari coal mine in 2006 and Gobindaganj in 2016, by institutional frameworks. The communities in Bangladesh rely heavily on their local biodiversity and natural resources for their livelihoods, treatment, aesthetics, and beauty. But their way of life is in danger due to climate change because it is changing their local environment and the quantity and quality of their resources. At the same time, the frequency and

intensity of natural disasters, such as floods and cyclones, destroy homes and crops and force communities to relocate.

Another meaningful impact of climate change on the Santals in Bangladesh is the increased frequency and severity of natural disasters. Natural disasters—such as the North Wester—destroy homes, crops, and other vital assets and force people to relocate. Climate change also affects the cultural practices and traditions of the Santals in Bangladesh. For example, deforestation (cutting off old and tall trees) threatens communities' sacred sites and cultural landmarks. This erodes their cultural identity and heritage and causes a loss of traditional knowledge and practices like the L'Bir rituals.

It is necessary to ensure that the voices of Santals are heard in decisions about climate policies and actions. This means ensuring that their voices and perspectives are considered when designing and implementing climate policies and that they can participate in decision-making processes at all levels. In this context, the Santals' rights need to be acknowledged and protected to address global climate change through global policy but local actions. Since Bangladesh's minorities—the Santals—typically lack means and capabilities (Sen 2009; Meadows et al. 1972), they need to adjust both pitfalls to changing environmental conditions to avoid severe susceptibilities in the community. However, they face multiple interrelated challenges, including food insecurity, displacement, loss of cultural heritage, and economic hardship, which undermine their livelihoods and well-being. To include their cultural diversity and consider their livelihoods, social systems, and cultural practices, international documents can relieve their social injustice.

One of the most urgent issues is that small Indigenous groups do not have self-determination rights for sustainable interventions. Nevertheless, to ensure Indigenous communities' sustainable livelihoods and create a culture of facing changing environmental collisions, GoB should pay attention to policy implications and institutional development.

To address atmosphere issues, policymakers should acknowledge the cultural and economic vulnerability before taking action to safeguard and preserve the Santals for future generations. This study hence proposes a probable solution—the Indigenous Community Perspective Model (Figure 2)—to ensure that the voices of Indigenous communities, for example, the Santals, are heard. Hearing their voices in climate policy and action decisions is vital. Indigenous groups in Bangladesh are experiencing complicated and wide-ranging effects of climate change, and efforts must be made to address these issues thoroughly and culturally. Indeed, there is a multifaceted approach that considers these communities' diverse needs and

circumstances and recognises the substantial role the community plays in developing solutions to climate crises.

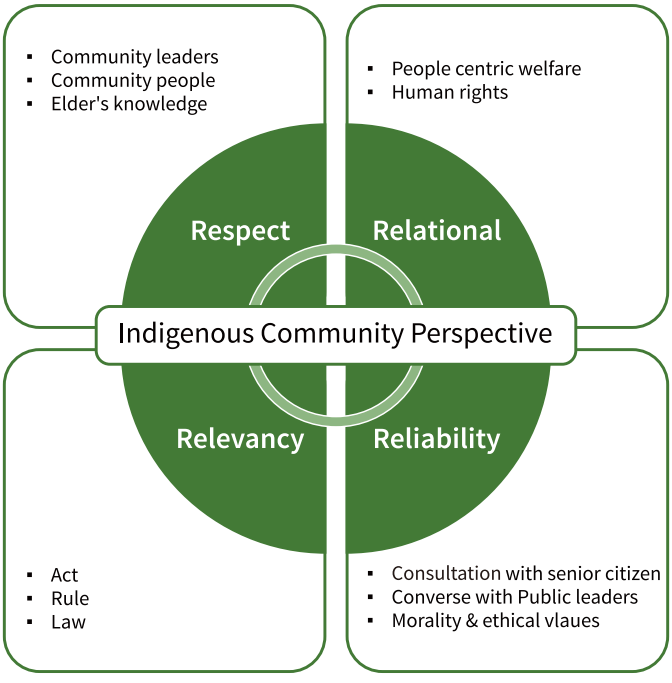


Figure 2. ICP Model for sustainable solutions to climate issues. Source: Figure by author.

Without aligning the 4 Rs (respect, relational, relevancy, and reliability), Indigenous people will not be able to face adverse climatic hazards at the community level.

5. Conclusions

Customary knowledge and local institutions are important in playing a meaningful role in countering climate issues. Local institutions empower communities to rapidly respond to environmental changes that threaten their traditional livelihoods, economies, practices, and lifestyles. Thus, to effectively address climate change, local perceptions, adaptations, and institutions must constitute an integral segment of national policies and action plans. The ICP model (Figure 2) provides sustainable solutions based on local knowledge and customary practices to understand Bangladesh's institutional drivers and constraints of climate policy reforms for the Santals. Addressing these constraints requires sustained political commitment,

stakeholder engagement, and investment in capacity building and knowledge generation through the ICP model.

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Climate Uncertainty Index for Pakistan and Its Nexus with Carbon Emissions and Growth

Mahrukh Rauf and Mumtaz Ahmed

1. Introduction

One of the most important issues of the modern era is climate change, which has an extensive worldwide impact. Its repercussions include changing weather patterns that undermine food security, rising sea levels that put coastal areas at risk, and a rise in the frequency and intensity of natural disasters. The United Nations (2020) states that if immediate action is not taken, the cost of adaptation in the future will increase significantly. Global carbon emissions must be drastically reduced if the worst effects of climate change are to be avoided. By removing carbon dioxide (CO_2) from the atmosphere, forests help to reduce these dangers. Forests can, however, become sources of emissions rather than sources of carbon when they are not properly maintained. The second-largest source of CO_2 emissions after fossil fuels, deforestation alone is responsible for about 13% of global emissions (Fahad and Wang 2020). Increased emissions lead to temperature extremes, altered rainfall patterns, ocean acidification, and worsening natural disasters

Long-term changes in temperature, precipitation, and other atmospheric parameters are referred to as climate change. The atmospheric temperature has risen dramatically during the Industrial Revolution due to human-induced greenhouse gas emissions (Stone et al. 2009). Like many other nations, Pakistan has seen a significant rise in CO_2 emissions, which has increased by more than 5.5% since 2010. This has resulted in significant socioeconomic losses and environmental damage (World Bank 2022).

Despite making up only 0.9% of the world's greenhouse gas emissions, Pakistan is one of the nations, most at risk from climate change. According to German Watch (2021), between 2000 and 2019, Pakistan was the 8th most-vulnerable nation to climate-related hazards. Frequent extreme weather events, like floods and glacial lake outburst floods, have resulted in a death rate of 0.3 per 100,000 people and economic damage of about USD 4 billion (Khan et al. 2016).

Pakistan's economy is growing quickly, and in the coming years, this trend will likely continue. The most important and prominent industry, agriculture, continues to be the foundation of the national economy. However, the rapid industrial boom in

Pakistan is causing the deterioration of agricultural land. Furthermore, deforestation is being caused by the rapidly expanding population. Pakistan is a leading Asian nation facing this issue. Increased industrialization and economic growth demand significant energy use, which has a negative environmental impact. According to the Environmental Kuznets Curve (EKC), CO_2 emissions will increase until economic growth hits a turning point, at which point they will start to decline. The relationship between CO_2 emissions and the growth of the economy is shown by an EKC curve as an inverted, U-shaped curve. The fundamental explanation of the EKC curve shows that, in the long run, encouraging economic growth does not contradict maintaining a clean environment (Salari et al. 2021).

Pakistan must act quickly to mitigate climate change because it is a developing nation with limited resources. Recently, tourism, both domestically and internationally, has significantly increased because of recent improvements to the northern areas' infrastructure and transport services. However, because of the increased human activity in these areas, millions of species are in danger and human survival is in jeopardy due to unprecedented exploitation. Rising temperatures have accelerated glacier melt, making floods caused by glacial lakes more likely, which endanger people living in these areas who are already lacking necessities. Pakistan's economy heavily depends on its land, which is climate-sensitive, and not only offers employment but also generates revenue from exports of agricultural products. Accordingly, the nation might suffer greatly from natural disasters (Taj 2022).

However, there are frequent environmental trade-offs associated with economic advancement. According to Erdoğan et al. (2019), rising energy consumption, which is essential to economic activity, is closely correlated with rising carbon emissions, which are the primary cause of climate change. This is echoed by Aftab et al. (2021), who point out that the current stage of global warming coincides with a period of notable industrial growth, underscoring the conflict between ecological sustainability and economic growth.

Climate change is inevitable as long as mankind emits greenhouse gases and carbon dioxide into the atmosphere. It is still unclear how quickly and precisely the atmosphere will react to these compositional shifts. There are still a lot of significant uncertainties in the relationship between future climate conditions and greenhouse gas emissions, despite efforts by the scientific community to quantify this. Although providing a basic indication of the severity of climate change, climate sensitivity provides little information about the precise times and places where variations in temperature are most likely to happen—information that decision-makers find vital (Heal and Millner 2014).

Three categories of uncertainty were identified by Hawkins and Sutton (2009) in terms of temperature projections: the initial condition, emissions scenario, and model uncertainty. Initial condition uncertainty arises from deviations in model forecasts due to slight modifications in the initialization of the models. Model uncertainty pertains to which climate model most accurately demonstrates the workings of the climate system. Unpredictability regarding future trends in greenhouse gas emissions is a component of emissions scenario uncertainty.

This research expands on the idea presented by Gavriilidis (2021), who created an index to measure climate policy uncertainty based on newspaper articles. In order to create this index, Gavriilidis analyzed eight major U.S. newspapers for the frequency of terms related to the climate, such as climate change crisis, carbon emissions, GHGs, greenhouse, and global warming. The number of articles containing these terms was scaled, and eight series were created from these newspapers and then normalized to develop the index, following the methodology proposed by (Baker et al. 2016). During the study period, there were multiple index spikes that corresponded with significant climate events during the sample period. Additionally, an empirical analysis was conducted to estimate the impact of carbon emissions on the index using a Vector autoregressive model. The outcomes showed that climate uncertainty significantly and adversely affects CO_2 emissions. Similarly, Lin and Zhao (2023) used the same methodology to use a textual evaluation to develop a climate policy uncertainty index for the cases of the USA, China, the UK, and India. A high level of correlation was found when this study evaluated the relationship between these four countries' climate uncertainty indexes. Additionally, the study used a VAR model to investigate the relationship between the GDP of these economies and the uncertainty related to economic and climate policy. The results demonstrated a relationship between economic policy uncertainty and climate policy uncertainty indices, with evidence pointing to the possibility that rising economic policy uncertainty could cause rising climate policy uncertainty.

This study differs from the previous research in two significant ways. First, it creates an index using monthly statistics from Google Trends for queries related to the climate, capturing the volume of internet searches for relevant terms. This index was created using the Generalized Dynamic Principal Component (GDPC) method. The second part of the study looks at the relationship between Pakistan's GDP, CO_2 emissions, and the climate uncertainty index.

The climate uncertainty index, based on data from Google Trends, has several advantages over the newspapers-based index proposed by (Gavriilidis 2021). First, this index is built on Google Trends, which is freely available. Hence, one very

attractive characteristic of the index is based on its easily obtainable survey of internet users. Second, associated with the previous advantage, it is downloadable, updated in a timely manner, and can be calculated easily. It has also been shown that this index can identify mood swings and the emotional state of people in a timely manner. Third, this index may reveal further private information in cases where there is no response to surveys and/or the incentive to tell the truth (Da et al. 2015). Fourth, this Index can also provide information from certain geographic areas (regions within and across countries) with varying degrees of growth. In addition, the wording of certain inquiries can be easily updated to reflect global variations.

2. Materials and Methods

2.1. Literature Review

The Climate Policy Uncertainty index was proposed by Gavriilidis (2021) for the USA, using the volume of major newspaper articles to effectively capture important climate policy events. The study finds that shocks to climate policy uncertainty are correlated with reductions in CO_2 emissions, both overall and within individual sectors. Bontempi et al. (2021) constructed an index of economic policy uncertainty using large-scale internet search data from Italy and the United States to evaluate political, economic, and normative uncertainty. This index considers actual interest in unclear subjects, as opposed to just media coverage, and determines the demand for knowledge between economic agents in reaction to uncertainty events. Ziabina et al. (2021) used Google Trends and a keyword co-occurrence analysis to examine energy conservation in the framework of national economic development, with an emphasis on carbon-free sources. Through an examination of 48,888 publications spanning the years 2000 to 2022, the authors ascertain that there is not enough agreement among researchers concerning the principal factors driving the nation's shift towards an economy free of carbon emissions. Researchers investigating factors influencing the rise in energy efficiency in national economies will find value in these findings.

Through sentiment analysis and analysis based on patterns of relative search volume (RSV) on social platforms, Lineman et al. (2015) investigated public knowledge of climate change (CC) and global warming (GW). Their research demonstrated a strong correlation between the public perception of these terms and information awareness, with greater public perception considerably increasing awareness. Additionally, depending on the situation, different people had different emotional reactions to these words. Further using Google Trends data, Lee et al. (2016) examined the global connectivity of interest in mitigating climate change in another study. Their 13-year study revealed an increasing trend of global interest

connectivity, with the US, Canada, and Japan being the main providers of influence on other nations' interest in climate change mitigation. The authors recommended giving priority to these top countries when promoting global climate change mitigation, as well as developing international policy approaches, based on their findings.

An et al. (2014) mentioned that public support is crucial for actions like reducing greenhouse gases and preparing for natural disasters; it is important to understand public perception. However, receiving real-time feedback through surveys can be tough and expensive. Twitter has become a major platform for discussing various topics, including climate change, making it a potential resource for studying public opinions. This paper explores whether mining data from Twitter can help us better understand how people perceive climate change, especially after experiencing climate-related disasters. It uses a mix of techniques, like analyzing text, assessing sentiments, and studying trends over time. The research encourages further investigation into these areas while also highlighting possible challenges. Loureiro and Alló (2021) suggested that the COVID-19 pandemic and climate change have a lot in common. However, in recent months, many climate adaptation and mitigation policies have been put on hold due to the health emergency. The study focuses on how the recent health crisis has affected the spread of information about climate change, along with other factors, like social norms and cultural aspects. To do this, they created a distinctive dataset that includes how many tweets contain particular keywords related to climate change in different countries, as well as each country's cultural influences, social norms, and socioeconomic traits. The findings show that socio-economic factors like income, education, and risk-related issues play a significant role in how climate change information is shared on Twitter. They also discovered that the COVID-19 outbreak notably reduced the volume of climate change-related messages, delaying the global discussion of climate change, especially in some vulnerable states. This indicates that regardless of the ongoing climate crisis, the epidemic negatively impacted short-term climate policy-planning in states where climate action is utmost needed.

Rana et al. (2022) investigated the rise in urban temperatures and the city's vulnerability to heat waves in Pakistan. In the Global South, their proposal for an index of localized heat wave vulnerability focused on sensitivity, exposure, and ability to adapt various parameters provides important information for disaster risk reduction and climate adaptation initiatives. Additionally, to evaluate the perception of climate change risk and glacial lake outburst floods (GLOF), Aslam et al. (2022) carried out a study on the Gilgit Baltistan area of Pakistan. Regression analyses and household surveys indicated that people perceived a higher risk of GLOF than they did of climate change. People's perceptions of GLOF were significantly influenced

by fear, while perceptions of climate change were influenced by factors like gender, level of education, lifespan, and prior hazard experiences. Developing community resilience against GLOFs and increasing public awareness require efficient strategies.

Another study was designed to examine worldwide scientific research on climate change over the past 18 years. It looked at trends, patterns, and methods in these research papers. The data, spanning from 1992 to 2009, were taken from the online Science Citation Index Expanded. The study analyzed articles on climate change by looking at the countries and institutes they came from, their titles, keywords, and abstracts, and the most-cited papers during the study period. The analysis of four types of keywords showed that, in the 21st century, the key topics in climate change research are environment, greenhouse gas, temperature, precipitation, and biodiversity, while a new method, called phylogeography, may become very useful soon (Li et al. 2011). According to (Salerno 2023), when people care a lot about certain issues, like during a big climate crisis, their opinions can strongly influence what the government does. One way to persuade the government to take action on climate change is by shaping public opinion. This study looked at how big news events affect how much people care about climate change. Google Trends has become a useful tool for measuring changes in public interest, but it only works well if we adjust the data. In 2019, because of the "Greta Thunberg effect", the countries responsible for taking action showed more concern than the ones most affected by climate change, which was a big change. This created a lot of pressure from the public for strong climate policies and other actions to tackle the climate crisis.

Hussain et al. (2020) reviewed 330 studies, including governmenta1 reports and news sources, to assess climate change mitigation and adaptation efforts in Pakistan and found that from 2012 to 2018, there was a significant reliance on thermal power generation, with minimal incorporation of renewable energy and a decrease in hydro energy. Despite awareness campaigns, CO_2 concentrations continued to rise, indicating inadequate governmental policies. The study emphasized the need to replace outdated technologies with cleaner methods and incentivize carbon capture processes. Meanwhile, Alvi et al. (2020) focused on perception, motivation, and attitudes toward energy-saving and climate change mitigation in Bangladesh and Pakistan. Their survey of 800 respondents in Dhaka and Islamabad revealed poor self-efficacy, cues to act, and benefit perception among citizens. Wealthier and more educated individuals, concerned about climate change's impact, were more inclined to adopt mitigation measures. The study recommended extensive awareness programs by governments to educate and motivate citizens about energy conservation and necessary mitigation actions in both countries.

2.2. Research Methodology and Data

In this study, the New Uncertainty-based Web Search method for queries associated with economic uncertainty (EURQ), as described by Bontempi et al. (2021), is used for Pakistan to propose the climate uncertainty index (CUI). As part of our methodology, we calculated the number of times a term related to climate was searched by utilizing Google Trends. Google is offering a free online tool called Google Trends that lets users examine search data to see how often particular queries are asked on the search engine operated by Google over time. This provides a graphical representation of the level of interest in specific keywords. Timeliness and geographic location can be utilized to focus the search. Although Google Trends provides insightful information, it has a number of drawbacks. It is less representative in areas with low internet access because its accuracy is dependent on the number and demographics of people who use the internet. While external factors may have an impact on long-term trends, the data is most suitable for short-term, real-time analysis. Cultural and geographic differences may also affect how data is interpreted. The use of data from these searches presents ethical and privacy issues, even though it is anonymized. Lastly, relying too much on Google Trends only may lead to skewed findings, emphasizing the necessity of using a variety of data sources and analysis techniques for more trustworthy results (Choi and Varian 2012).

The key difference between our index and the one proposed by (Gavriilidis 2021) is that rather than using extracted keywords from newspaper articles, we used Google search for our research. This allows data to be directly extracted from an individual. The observation of an individual's interest prevents any third-party perception from being included in the study. We used terms that were similar to those in the newspaper-based CPU index, but while using these terms, we replaced the frequency of articles with the intensity of Google searches, which shifted the focus from media representation to personal interest.

Monthly data from January 2004 to December 2021 was used to create this index. The terms and queries used in previous research by (Gavriilidis 2021) on measuring uncertainty regarding climate, as well as keywords taken from other climate-related articles and studies, are all included in the table below. At first, 56 keywords were extracted to develop the index (Table 1). However, after careful observation, it was observed that 11 keywords had an extremely low volume of searches—those marked with an asterisk (*) sign in Table. This left us with 45 keywords that were used to create the climate uncertainty index. Data from Google Trends was obtained through web-scraping. We developed a Python Pytrends module to download Google Trends data for the set of keywords in Table 1 from January 2004 to December 2021.

Table 1. Keywords obtained from Google Trends.

S. No.	Keywords	S. No.	Keywords
1	Afforestation	29	Environmental law
2	Atmospheric temperature	30	Environmental policy
3	Biodiversity	31	Environmental protection
4	Bioenergy	32	Environmental risk *
5	Burning coal	33	Floods
6	Burning fuel	34	Forest fires *
7	Carbon dioxide	35	Fossil fuel *
8	Carbon footprint	36	Global environmental change
9	Carbon intensity *	37	Global warming *
10	Chlorofluorocarbons	38	Green energy
11	Climate	39	Greenhouse effect
12	Climate change	40	Greenhouse gas emissions
13	Climate change adaptation	41	Heat stress *
14	Climate change crisis	42	Heat wave
15	Climate change effects	43	Humidity
16	Climate disaster	44	Methane
17	Climate policy	45	Natural disaster
18	Climate risk	46	Nitrous oxide *
19	Cloud burst	47	Ocean acidification *
20	CO_2	48	Ozone depletion
21	Combustion	49	Ozone layer
22	Cop26 *	50	Plantation
23	Deforestation	51	Renewable energy
24	Drought	52	Sea level rise *
25	Ecosystem	53	Smog
26	Emissions	54	Solar energy
27	Environment	55	Temperature
28	Environmental degradation *	56	Weather change

Note: An asterisk sign (*) at the end of a keyword indicates a low search volume; thus, this keyword was excluded when constructing the index. Source: Table by authors; based on previous literature and already-available climate-related indices.

To fulfil the study's secondary goal, which involves estimating the relationship between GDP, CO_2 emissions, and the CUI of Pakistan, the World Bank database provided the secondary data source for GDP per capita and CO_2 emissions per capita for the years 2004–2021. Due to the unavailability of monthly data on GDP and CO_2 emission, we upgraded the index to an annual frequency before the empirical analysis.

2.2.1. Generalized Dynamic Principal Component (GDPC)

This study includes the construction of a climate uncertainty index (CUI) using GDPC, implemented through an R code (R-Language (This works on R version 3.3.0 or higher)). The main reason behind creating an index using GDPC was to obtain a more accurate index, as GDPC has more advantages than a rival approach, conventional principal component analysis (PCA). The GDPCA approach differs from Brillinger's method in three ways in defining dynamic principal components. First, the series of generalized dynamic principal components (GDPC) is constructed without assuming that the series has stationarity. In contrast to Brillinger's method which aims to minimize the expected reconstruction MSE, the GDPC reduces the meaningful reconstruction criterion, for the case, when series under examination is non-stationary. GDPC need not be a linear combination of original series. Thirdly, rather than working in the frequency domain, it works directly in the time domain. GDPC can be used for data compression to reduce the resources needed for data transmission and storage, signifying its use in spatial statistics where dependence is significant in the compression of dependent data (Peña and Yohai 2016).

Let us take a time series vector, $y_t = y_{1,t}, \ldots, y_{m,t}$, where $1 \leq t \geq T$. Let Y be the $T \times m$ matrix with rows $y_1, \ldots, y_T$, where T is the number of periods and m denotes the number of series. The first dynamic principal component is defined as a vector:

$$f = (f_t), \; k+1 \leq t \geq T$$

where k = number of lags, so that the mean squared error (MSE) criterion is satisfied when series $Y_{j,t}$, $1 \leq t \geq T$ is reconstructed as a linear combination of $(f_{t-k}, \ldots, f_{t-1}, f_t)$. In more detail, the reconstruction of the initial series, $Y_{j,t}$ is defined as

$$y_{j,t}^{R,b}(f, \beta, \alpha) = \alpha_j + \sum_{h=0}^{k} \beta_{j,h+1} f_{t-h} \tag{1}$$

Considering a potential factor of length $(T+K)$ and $m\text{x}(K+1)$ matrix of coefficients $\beta = \left(\beta_{j,h}\right)$, $1 \leq j \leq m$, $1 \leq h \leq k+1$ and $\alpha = (\alpha_1, \ldots, \alpha_m)$.

In $y_{j,t}^{R,b}$, R represents reconstruction, b represents backward because reconstruction was determined through applying lags of f_t, contraste$b$ with the later-described lead-based reconstruction. While reconstructing the m series with f, β and α, MSE is

$$MSE\left(f,\beta,\alpha\right)=\frac{1}{Tm}\sum_{j=1}^{m}\sum_{t=1}^{T}\left(z_{j,t}-z_{j,t}^{R,b}\left(f,\beta,\alpha\right)\right)^{2} \tag{2}$$

This yields $\hat{f}$,$\hat{\beta}$,$\hat{\alpha}$ as the values that minimize MSE.

Since the model remains the same when we divide f_{t-h} by the same constant and multiply $\beta_{j,h+1}$ by a constant, the value of $\hat{f}$ is not known. Further, using $\hat{f}$ with a mean zero and unit variance, the first GDPC is $\hat{f}$. The principal component of data that is ordinary and non-dynamic is $\hat{f}$, where $k = 0$. The first GDPC of the residuals is the definition of the second GDPC, given by

$$r_{j,t}=z_{j,t}-z_{j,t}^{R,b}\left(\hat{f},\hat{\beta},\hat{\alpha}\right),\ 1\leq j\geq m,\ 1\leq t\geq T$$

Similar definitions are used for higher-order GDPC. Note that the reconstruction of Equation (1) can be written by using leads rather than lags (Peña et al. 2020).

2.2.2. Unit Root Test

To achieve the second objective, a Vector Autoregressive (VAR) model is used to analyze the relationship between the climate uncertainty index (CUI), GDP, and CO_2 emissions. Before applying the VAR model, it is good to check the stationarity of all variables (Chang and Park 2003). This is achieved by applying Augmented Dickey–Fuller (ADF), proposed by Dickey and Fuller (1979, 1981). The null hypothesis of ADF is that each underlying series has a unit root at this level. The alternative hypothesis states that the series does not contain a unit root at the level.

For a given time series, Y_1 , Y_2 , $\ldots, Y_N$, ADF suggests three different specifications:

$$\Delta Y_t \;=\; \gamma Y_{t-1} \;+\; \sum_{j-1}^{p}\left(\delta_j\,\Delta Y_{t-j}\right)+\;e_t$$

$$\Delta Y_t \;=\; \alpha+\gamma Y_{t-1} \;+\; \sum_{j-1}^{p}\left(\delta_j\,\Delta Y_{t-j}\right)+\;e_t$$

$$\Delta Y_t \;=\alpha+\beta t+\;\gamma Y_{t-1} \;+\; \sum_{j-1}^{p}\left(\delta_j\,\Delta Y_{t-j}\right)+\;e_t$$

where t is time index, intercept is α, and the coefficient of the time-trend is β, while γ shows the coefficient of the first lag of Y_t , and p indicates the optimal number of lags chosen via AIC. Finally, the white noise error term is denoted by e.

2.2.3. Vector Autoregressive Model (VAR)

The VAR framework treats every variable as endogenous, implying everything affects everything else and there are very few truly exogenous variables. It can make accurate predictions and the related impulse response functions, which are computed based on the moving average representation of the VAR model, can be used to track the impact of policy changes (Hatemi-J 2008). The study employs the Vector Autoregressive (VAR) model to assess the relationship among the climate uncertainty index (CUI), GDP, and CO_2 emissions by making use of annual time series data from 2004 to 2021.

Let $Z_t = \begin{bmatrix} CUI_t \\ CO_{2t} \\ GDP_t \end{bmatrix}$ be a 3×1 vector associating CUI_t, CO_{2t}, and GDP_t; then, the $VAR\,(p)$ is

$$Z_t = A_0 + \sum_{i=1}^{P} A_i Z_{t-i} + \varepsilon_t \tag{3}$$

where ε_t is white noise error, $A_i's (i = 1, 2, \ldots, p)$ are coefficient matrices, and p is the lag-length. Equation (3) can be written in a more simplified form for $p = 1$ as

$$CUI_t = a_{01} + a_{11} CUI_{t-1} + a_{12} CO_{2t-1} + a_{13}\ GDP_{t-1} + \varepsilon_{1t}$$

$$CO_{2t} = a_{02} + a_{21} CUI_{t-1} + a_{22} CO_{2t-1} + a_{23}\ GDP_{t-1} + \varepsilon_{2t}$$

$$GDP_t = a_{03} + a_{31} CUI_{t-1} + a_{32} CO_{2t-1} + a_{33}\ GDP_{t-1} + \varepsilon_{3t}$$

where it is assumed that error terms across the above three equations in VAR(1) do not correlate contemporaneously.

An impulse response function provides the evolution of a variable over a given time horizon in response to an external shock (usually called an impulse) in a specific time period (United Nations 2016). The VAR model is estimated and related impulse responses are generated by an innovation of 1 SD.

3. Empirical Results

3.1. Climate Uncertainty Index Construction

Search engines and social networking site data may offer intriguing insights into public interest patterns and trends related to environmental issues, but only after a rigorous evaluation and validation procedure. This section includes the climate uncertainty index (CUI) of Pakistan, created based on the searched volume of the keywords obtained from Google Trends (Table 1).

Figure 1 shows the climate uncertainty index (CUI) constructed via PCA for non-normalized (a) and normalized data (b), while the same index was constructed via conventional PCA for non-normalized (c) and normalized data (d). Note that conventional PCA is used as a comparison and robustness check for the newly introduced novel GDPCA approach. For the second objective, we used the climate uncertainty index constructed via the GDPCA method due to its several advantages over the conventional rival.

Table 2. Results of the ADF test.

Variable	At Levels		1st Difference	
	ADF-Statistic	*p*-Value	ADF-Statistic	*p*-Value
CO_2 emissions	−0.611	0.8436	−2.636	0.1064
CUI	−5.93	0.0001	-	-
GDP	−0.525	0.863	−3.361	0.029

Source: Table by authors.

3.2. Unit Root Testing

The results of the ADF unit root test are provided in Table 2. The findings in Table 2 suggest that CUI is stationary at levels, while both CO_2 emissions and GDP are non-stationary at levels but first show a difference. Thus, one can say that CUI is integrated in order 1, while both CO_2 emissions and GDP are integrated in order 2. During VAR, these non-stationary series were converted to stationary by taking their first difference.

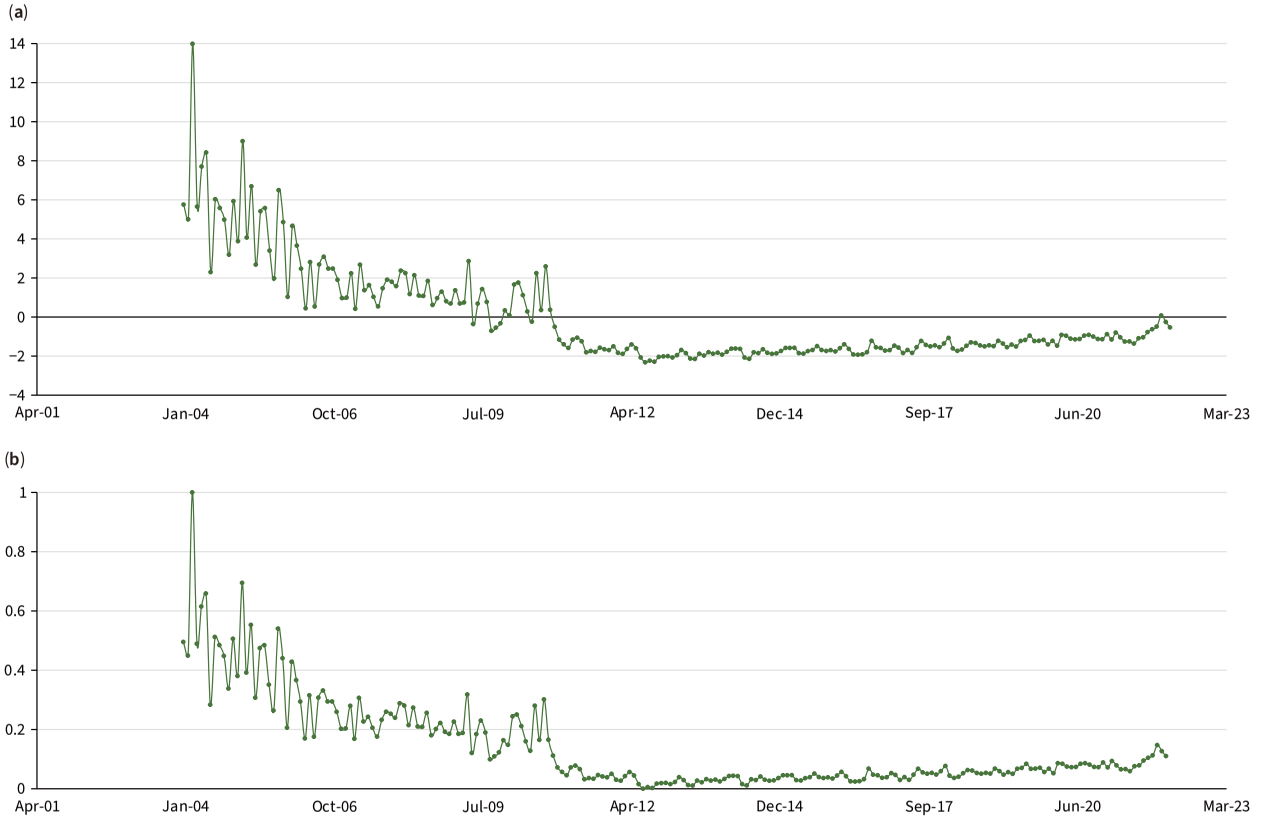


Figure 1. *Cont.*

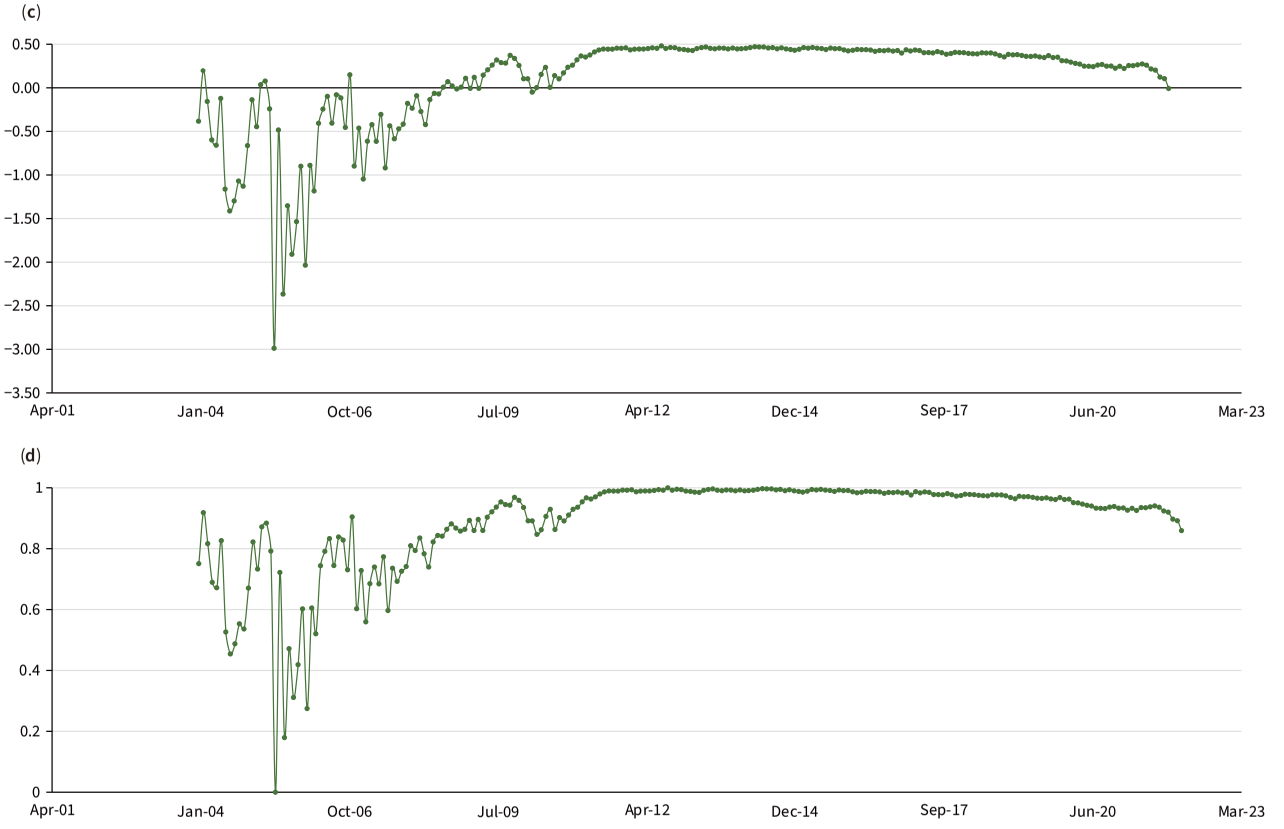


Figure 1. Climate uncertainty index for Pakistan. (**a**) Climate uncertainty index using PCA (non-normalized data); (**b**) climate uncertainty index using PCA (normalized data); (**c**) climate uncertainty index using GDPCA (non-normalized data); (d) climate uncertainty index using GDPCA (non-normalized data). Source: Figure by authors.

3.3. Estimation of VAR Model

The next step is to use the VAR model to assess the relationship between all three candidate variables. The order of VAR is chosen via AIC, resulting in the VAR(1) model (Table 3).

Table 3. Results of the VAR(1) model.

Variable	Dependent Variable		
	CO_2	CUI	GDP
Constant	−0.0008	−0.12	−307.3
	(0.01)	(0.12)	(1224.3)
	[−0.04]	[−1.01]	[−0.25]
$CO_2(-1)$	−0.12	−1.74	−1441.3
	(0.30)	(2.25)	(21,659.1)
	[−0.38]	[−0.77]	[−0.06]
CUI(−1)	0.009	−0.56	85.04
	(0.01)	(0.12)	(1191.2)
	[0.58]	[−4.53]	[0.07]
GDP(−1)	−9.26	−5.45	0.58
	(6.30)	(4.60)	(0.44)
	[−0.14]	[−1.18]	[−1.88]
Adj R-squared	0.21	0.56	0.09
S.E. equation	0.06	0.47	4564.3
F-statistic	0.17	7.17	0.61
Log likelihood	−22.04	−7.77	−145.3
Akaike AIC	−2.40	1.57	19.9

Note: SEs in ( ) and *t*-stats in [ ]. Source: Table by authors.

3.4. Impulse Response

The impulse response functions provided in Figure 2a–f are generated, showing one SD innovation (shock) with ±2SE error bands using asymptotic SEs. Specifically, Figure 2a presents the response of CUI when one SD shock is given to CO_2. The impact is negative in periods 1–2. After the second period, the index shows a rise in periods 2–3. After the third period, there is a decline in the CU index until the fourth

period, which shows more uncertainty, but later, in period 6 onward, it converges back to 0 and the effect of the innovation dies out.

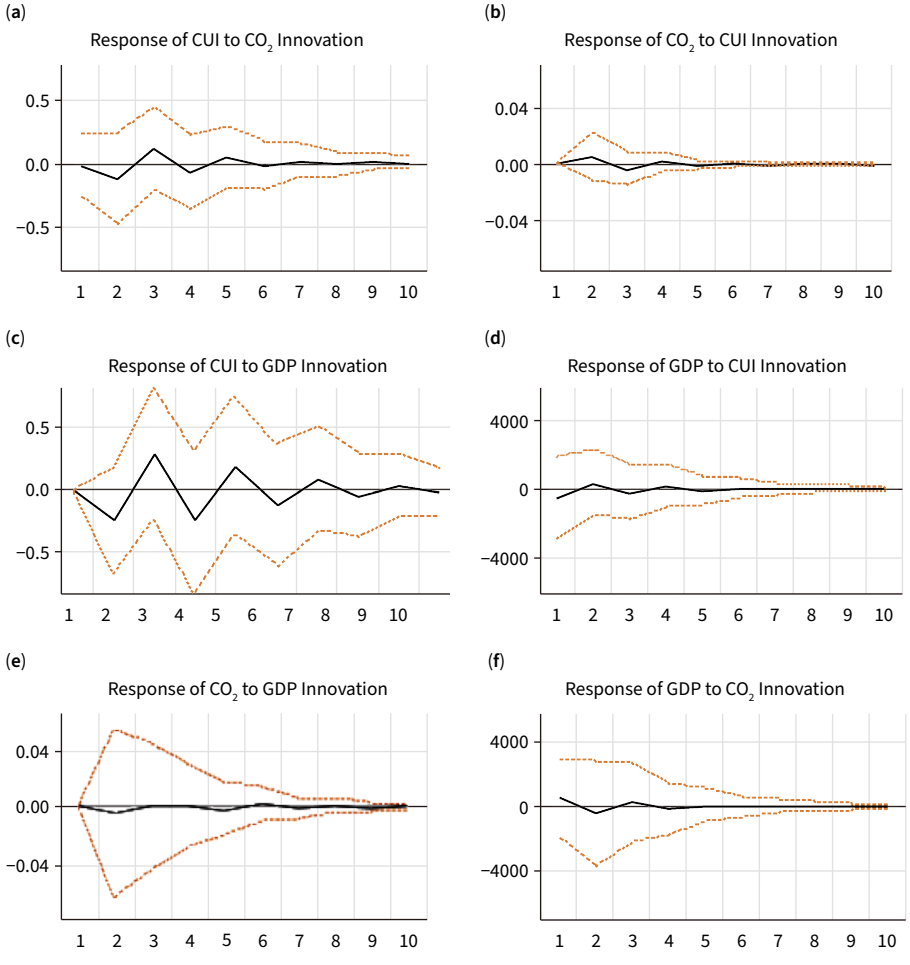


Figure 2. Impulse response functions for a unit SD innovation. Source: Figure by author.

Figure 2b shows the response of CO_2 when one SD shock is given to CUI. It is noted that CO_2 is positive at first, then keeps changing, but ultimately converges back to 0. In short, Figure 2a,b show that CO_2 emissions have a strong and negative impact on the climate uncertainty index. However, if there is an innovation of one SD in climate uncertainty, a positive impact can be seen on CO_2 emissions. More uncertainty regarding the climate leads to an increase in CO_2 emissions.

Figure 2c shows the impact of one SD shock on GDP to CUI indicating that a one SD shock in Pakistan's GDP lowers the climate uncertainty in periods 1–2. Then, there is a rise in the climate uncertainty index from periods 2–3 and a sharp decline from period 3 to four, showing more uncertainty. Due to a shock to Pakistan's GDP, the country's climate uncertainty index fluctuated for five periods before returning to zero. The impact of the shock on GDP to CUI matches the impulse response of the previous study by Lin and Zhao (2023), in which a newspaper-based approach was applied.

Figure 2d portrays that the impact of one standard-deviation shock in the climate uncertainty index on the GDP of Pakistan. Initially, a shock of one SD on the climate uncertainty index leads to an increase in GDP for one period; after that, it decreases from period 2 to period 3, but after period 4, the effect of shock dies out.

Figure 2e shows the impact of a unit shock to GDP on CO_2 suggesting a negative impact on CO_2 emissions but for a short period, and after that, it starts to increase and converges back to 0. In Figure 2f, an impulse response of a unit SD shock to carbon emissions shows a negative impact on GDP in early periods but then it fades out.

4. Discussion

The aim of this study was to fill the knowledge gap and create a climate uncertainty index (CUI) for Pakistan, for the first time to the best of the authors' knowledge, by quantifying public concerns and uncertainties about climate issues in Pakistan. In addition, the study examines the nexus among climate uncertainty, CO_2 emissions, and economic growth for Pakistan. Specifically, the CUI is constructed by employing state-of-the-art generalized dynamic principal component analysis (GDPCA) and the conventional PCA method. GDPCA has the advantage of working well even when the data series are non-stationary over the conventional PCA.

Furthermore, this newly developed index may help practitioners in assessing its relationship with other related variables other than CO_2 emissions and economic growth. It is essential to consider the associated uncertainties as well as risks related to climate activities while assessing the impact of climate change on economic as well as financial markets. The policy decisions made by governments related to climate change are characterized by substantial uncertainty in terms of their nature, impact, and timing. As shown in Lee and Cho (2023), the climate policy uncertainty and climate uncertainty indices (developed using Twitter-based data for China) indicate an increase because of a variety of events such as alerts about glaciers melting in China, conferences about climate change by the United Nations, and presidential declarations on climate change.

As a second objective, the present study makes use of a vector autoregressive model to examine the relationship among carbon dioxide emissions, economic growth, and the CUI. The empirical findings highlight significant dynamics of the developed climate uncertainty index. Any external shock that raises climate uncertainty is linked to an increase in CO_2 emissions, indicating that increased uncertainty could make it more difficult to take effective environmental action. On the other hand, climate uncertainty tends to decrease with a positive shock to GDP growth, suggesting that economic stability may help ease people's concerns of climate threats. It is interesting to note that rising levels of the climate uncertainty index themselves seem to boost economic expansion in Pakistan, which demonstrates the intricate relationships between economic activity and perceptions of the climate.

The positive relationship between economic growth and the CUI suggests that any shock to the CUI—for example, an increase in climate uncertainty—may lead the government to promote short-term economic activity, say by increasing expenditure on disaster relief, infrastructure, and green energy. A higher level of climate uncertainty may also impact the behavior of businesses and consumers, where consumption may increase in the short term rather than saving for the long term. It may help in attracting foreign climate finance, boosting economic growth. This indicates the importance of the climate uncertainty index, which paves the way for uncertainties associated with the climate's impact on environmental outcomes and economic growth.

5. Conclusions

Predicting climate uncertainty is central in the environmental literature. Compared to developed nations, developing nations like Pakistan, whose economy depends heavily on agriculture, are more vulnerable to the effects of climate change. Climate change is simultaneously causing flooding, temperature increase, sea level rise, and droughts in Pakistan. Quantifying the overall level of uncertainty related to climate change is extremely important because it aids decision-making for investors and policymakers. This study takes the lead and develops a new climate uncertainty index (CUI) for Pakistan based on Google Trends monthly data on several important keywords related to climate. An important advantage of this index over the existing index developed by Gavriilidis (2021) for the US is that instead of using keywords extracted from newspaper articles, the intensity of Google searches is used, allowing a direct extraction of data from individuals rather than a third-party perception, thus shifting focus from media representation to personal interest. In addition, the nexus between CUI, CO_2 emissions, and growth via a VAR framework and the related

impulse response functions is examined. The results of the analysis indicate that any external shock to climate uncertainty leads to an increase in CO2 emissions. Further, a shock in GDP (growth) will lead to a decline in climate uncertainty, but a shock in CUI will lead to an increase in the growth of Pakistan.

The climate uncertainty index developed using Google Trends provides policymakers with a useful, up-to-date tool for measuring public concern related to climate issues. Including this index in systems for early warning can assist governments in predicting public responses during high-risk events, such as extreme heat waves or monsoon periods. A timelier allocation of resources and emergency preparedness for disasters may result from this. Moreover, the impact of outreach could be enhanced by scheduling campaigns to raise public awareness during times when search activity is at its highest. Climate action plans that are location-specific and targeted may also be influenced by regional CUI trends.

Despite its useful insights, the CUI has drawbacks. It may not include people who live in remote areas or who are not connected to the internet because it only records the behavior of internet users. Media coverage or world events may influence local interpretations, and Google Trends shows a relative rather than an absolute search interest. Over time, algorithm changes may also have an impact on data consistency. To increase the index's credibility, future studies could compare it to survey results or timelines of climate events. A comparative analysis could be possible if the index is extended to other nations. While incorporating social media data can improve its responsiveness and depth, machine learning can also improve keyword selection. These actions will make the CUI more acceptable and reliable as well.

This study concludes that relatively expensive and logistically difficult survey techniques have been used to examine the behaviors, expertise, and perspectives of citizens and important decision-makers; however, our study encourages researchers to use platforms such as Google trends, social media platforms, and Twitter for data collection, which shows direct opinions of the public, and determine public interest in a particular topic. These platforms can also be used for analysis of opinions and time series methods. Additionally, the climate uncertainty index will be helpful in future research to investigate the effects of climate uncertainty on energy consumption and GHG emissions. Another promising research area is the examination of how uncertainty in climate policy affects businesses in climate-vulnerable sectors, such as transportation, energy, and mining. To sum up, our study highlights the significance of considering climate uncertainty in thorough evaluations of climate change and

policy development, opening the door to better inform individuals of and implement practical approaches to one of the most critical issues of our day.

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Financing the Transformation into the World's First Climate-Resilient Country: The Climate–Debt Nexus in Dominica

Jwala Rambarran

1. Introduction

Developing countries require considerable amounts of finance to invest in climate resilience and low-carbon transitions. The Independent High-Level Expert Group on Climate Finance estimates that developing economies (excluding China) will need around USD 2.4 trillion of climate finance per year by 2030, of which USD 1 trillion per year is external finance (Songwe et al. 2022). From a developed country's perspective, Bolton et al. (2024) argues that although providing this considerable volume of climate finance to developing countries is both economically desirable and feasible, it is not happening at the necessary scale due to the free-rider problem across donor countries, affordability issues—even for advanced economies—and the required conditionality may not be feasible to ensure that climate finance achieves its intended purpose.

Further, many developing countries face a climate–sovereign debt doom loop (Zenios 2022). Climate-related disasters force these countries to borrow heavily to finance recovery efforts, worsening their debt situation and limiting the resources they need to invest in climate resilience, while their borrowing costs are rising partly due to climate-related vulnerabilities, leading to more debt (Alayza et al. 2023; Decitre et al. 2025). The challenges associated with this climate–debt nexus are particularly acute for Dominica. Not only does Dominica have substantial challenges in financing its transformation to become the first climate-resilient nation in the world, but its high indebtedness also limits its borrowing capacity to fund its climate resilience ambitions.

Following the catastrophic devastation caused by Hurricane Maria in September 2017, Dominica set an extremely ambitious vision to rebuild as the world's first climate-resilient nation (GoCD 2018). However, successfully financing its recovery and resilience to future climate events depends on Dominica's ability to effectively mobilise substantial volumes of climate finance, which not only far exceed the country's domestic capacity but are also well beyond the modest amounts of grants and concessional funding it receives from traditional development partners. Further

complicating the situation is the fact that Dominica's elevated debt ranking amongst the top ten most heavily indebted Small Island Developing States (SIDSs) severely constrains the country's fiscal space and additional borrowing.

According to the Dominica Climate Resilience and Recovery Plan 2020–2030, Dominica requires at least USD 3.5 billion by 2030 to achieve its vision to become climate-resilient. Of this amount, the government has already invested close to USD 1 billion between 2018 and 2024 to fund public investment in hurricane-resistant houses and public buildings, roads and bridges, water infrastructure, and emergency shelters. Based on current government capital expenditures, an additional USD 1 billion could be available for further investment in climate-resilient initiatives till 2030 (GoCD 2024a). This leaves Dominica with an estimated wide climate funding gap of around USD 1.5 billion between 2025 and 2030, or about USD 300 million annually to 2030—the equivalent of 40 percent of the country's 2024 GDP each year.

So far, the Dominican government has been relying mainly on non-tax revenues associated with its Citizenship by Investment (CBI) programme and foreign borrowing to fund its climate resilience projects. However, the IMF has cautioned the Dominican authorities against the growing reliance on CBI revenues to finance capital spending, advising that the government should be mindful of the volatile and unpredictable nature of these capital flows, which can come to a sudden stop (IMF 2017b). Moreover, Dominica's high public debt makes further borrowing even more difficult. Heavy external borrowing to rebuild after Tropical Storm Erika and Hurricane Maria pushed Dominica's public debt from 72 percent of GDP in 2014 to a peak of 113 percent of GDP in 2020. By the end of 2023, Dominica's debt stood at over 97 percent of GDP, ranking Dominica as the fifth most heavily indebted SIDS in the world. Rapid debt accumulation has led to rising debt service payments, which are draining resources away from Dominica's ability to deliver on other United Nations Sustainable Development Goals (SDGs).

Given the challenges of the intertwined climate–debt nexus facing Dominica, this Chapter analyses the potential climate financing solutions that Dominica could pursue to help fund its vision to become the world's first climate-resilient country without further pushing it into debt distress. This Chapter is organised as follows: following the introduction in Section 1, the discussion in Section 2 makes the case for building climate resilience in Dominica. Section 3 describes some of the main climate financing mechanisms which Dominica could implement to fund its climate transition and adaptation projects. Finally, this Chapter concludes in Section 4 with policy implications and areas for future research.

2. The Case for Building Climate Resilience in Dominica

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) underscored that developing countries are likely to be significantly more exposed to the negative impacts of chronic and acute physical climate risks (IPCC 2021). Beyond these physical risks, a country could also be affected by transition risk, that is, a disorderly introduction of climate policies and regulations (NGFS 2019). Mitigating and adapting to both physical and transition risks require developing countries to scale up public and private capital for climate investments (Kreibiehl et al. 2022), but mobilising such volumes of climate finance is particularly challenging for these countries due to their limited fiscal space and restricted or costly access to international capital markets (OECD 2021). As a Caribbean SIDS, Dominica not only faces exposure to physical and transition climate risks but also the difficulty of mobilising sufficient volumes of low-cost climate finance. These challenges stem from the specific characteristics of SIDSs, such as geographic location, small landmass, small population, small economic size, and high vulnerability to economic shocks (World Bank 2016).

Dominica's geographical location within the North Atlantic hurricane belt exposes the small island to physical climate risks, most notably the impact of tropical storms and hurricanes. Dominica is also exposed to storm surge, sea level rise, flooding, and drought. These physical risks could negatively affect Dominica's public finances through lower tax revenues and public debt accumulation (Lugay and James 2014), worsen the balance of payment stability, and adversely impact other sectors, such as agriculture, which is critical to the island's food security. According to the EM-DAT (2025) database, which records natural disasters throughout the world, 14 tropical storms and hurricanes hit Dominica between 1963 and 2024, killing some 139 persons, affecting almost 195 thousand through injury and loss of homes and livelihoods, and causing loss and damage worth almost USD 2.3 billion (Table 1).

Table 1. Dominica: loss and damage from selected tropical storms and hurricanes, 1963–2024.

Year	Event Name	Impact	Loss and Damage	
			USD '000	Percent of GDP
1963	Hurricane Edith (Category 1)	Agriculture	2600	n.a.
1979	Hurricane David (Category 4)	Major devastation	44,650	20

Table 1. *Cont.*

Year	Event Name	Impact	Loss and Damage	
			USD '000	Percent of GDP
1980	Hurricanes Federick and Allen (Category 1)	Economy Agriculture	16,300	22
1984	Hurricane Klaus (Category 1)	Infrastructure	2000	2
1989	Hurricane Hugo (Category 4)	Agriculture Forestry Fishing	25,555	14
1995	Tropical Storm Iris Hurricane Marilyn (Category 1) Hurricane Luis (Category 1)	Agriculture Housing Flooding	195,000	70
1999	Hurricane Lenny (Category 4)	Coastal damage Sea surge 30–40 feet	29,858	9
2007	Hurricane Dean (Category 2)	Agriculture Housing	21,069	5
2008	Hurricane Omar (Category 4)	Coastal damage Sea surge 20–30 feet	n.a.	n.a.
2015	Tropical Storm Erika	Housing Infrastructure	482,810	95
2017	Hurricane Maria (Category 5)	Total devastation	1,456,000	226

Note: n.a. means not available. Source: Author's compilation based on data from EM-DAT (2025).

In the past decade alone, Dominica has been hit by two extreme weather events.[1] Tropical Storm Erika struck the island on 28 August 2015, causing heavy rainfall, flooding, and landslides. In its wake, 30 persons died, 22 people were missing, approximately 10 percent of the population was affected, and the community of

[1] Apart from the shocks associated with these two hurricanes, Dominica has also been hit by two other successive large shocks within the past decade. These shocks were the global COVID-19 pandemic, which erupted in 2020, and Russia's war on Ukraine, which started in early 2022.

Petite Savanne was destroyed (GoCD 2018). Tropical Storm Erika resulted in a total loss and damage equivalent to around 95 percent of Dominica's 2014 GDP (IMF 2018). Two years later, with the post-Erika recovery efforts underway, the second extreme weather event to hit Dominica was Hurricane Maria, which made landfall on 18th September 2017 as a powerful Category 5 hurricane (NOAA 2023). In its wake, it left 65 people dead and 37 missing; 80 percent of the population was affected. Most of the island's physical infrastructure was damaged or destroyed (GoCD 2020). Power, water, and telecommunication services were disrupted for several months. The extensive devastation across Dominica from Hurricane Maria amounted to an estimated 226 percent of the country's 2016 GDP (IMF 2018). Maria was the worst natural disaster that the world had seen in terms of loss and damage in percentage of GDP (IMF 2018), and it imposed significant costs on the Dominican economy, including a substantial loss of output, increased spending on rehabilitation and reconstruction, a sharp deterioration in fiscal and external accounts, and increased debt (Thomas and Theokritoff 2021).

Climate projections performed by the Climate Studies Unit of the University of the West Indies, Mona, for the Caribbean Development Bank (CDB 2020) suggest that, as the century progresses, the Caribbean region will be prone to more intense tropical storms. Further, projections performed by Climate Analytics (2024) show that the relative change in expected annual damage from tropical storms in Dominica is expected to increase by 6 percent at 1.5 °C global warming, 14 percent at 2 °C, and 29 percent at 3 °C, as compared to a baseline of 2020. On this basis, Dominica could become more vulnerable to the impact of physical climate risks in the future, which may sharply affect its macroeconomic stability and debt sustainability prospects.

Dominica has leveraged its extensive natural resources, such as tropical rainforests, marine life, volcanoes, sulphur lakes, and coral reefs, to develop a distinct eco-tourism brand as the 'Nature Island' of the Caribbean. Tourism's broader (direct and indirect) contribution was estimated at over 30 percent of the country's GDP (WTTC 2019). Climate risks could affect Dominica's dominant tourism sector in two ways. The first is through transition risks; international air travel is a main contributor to global greenhouse gas (GHG) emissions (IPCC 2021) and is subject to large decreases in all low-carbon transition scenarios, at up to 90 percent by 2050 (IEA 2021). This suggests that Dominica could face a substantial reduction in the volume of tourists over the next few decades. Second, physical climate risks are increasingly impacting Dominica's tourism sector. According to Roberts (2019), most of the island's tourism infrastructure (hotels, diving industry, and yachting) along the southwest and west coasts are situated close to the shore or in low-elevation

coastal zones and are at flooding risk due to rising sea levels and higher storm surges. In addition, rising sea surface temperatures since late 2023 have led to another mass coral bleaching event across the wider Caribbean region, which is also impacting Dominica's coral reef eco-system, a major attraction for the island's niche scuba diving market. A decline in the eco-tourism industry from these impacts of climate change would negatively affect Dominica's debt sustainability, as well as its economic growth, employment, public finances, and financial stability.

Like other Caribbean SIDSs, Dominica has historically contributed very little to global warming but is heavily dependent on fossil fuels for its energy needs. This contributes to widening Dominica's trade and current account deficits, puts pressure on foreign exchange reserves, makes it extremely vulnerable to volatility in international energy prices, and increases the island's transition risks. Imported petroleum fuels for electricity generation, gasoline for transportation, and liquefied petroleum gas (LPG) for cooking gas in households contribute to negative environmental and health impacts such as noise, poor air quality (especially in transport), and contamination due to spills and waste disposal (GCF 2022), all of which are inconsistent with Dominica's Nature Island brand image. By 2024, fuel imports had increased to around USD 55 million, up from USD 30 million in 2019, reflecting the high and rising cost of fuel imports following Russia's war on Ukraine and the Israel–Hamas conflict. Dominica, however, needs to access sufficient volumes of climate finance for its transition to renewable energy via monetizing the country's significant geothermal energy resources. Dominica is a young volcanic island with the highest concentration of active volcanoes in the Eastern Caribbean, although eruptions are rare. According to the National Renewable Energy Laboratory (2015), Dominica has a minimum of 300 MW of geothermal power potential, or at least 5 times its projected power demand. In 2022, about 30 percent of Dominica's electricity demand was met by hydroelectric power generated from geothermal resources.

Although Tropical Storm Erika and Hurricane Maria severely tested Dominica's climate adaptation preparedness (GCF 2022), the country demonstrates a relatively high readiness to enhance its climate resilience. The ND-GAIN Country Index, a project of the University of Notre Dame Global Adaptation Initiative (ND-GAIN), summarises a country's vulnerability to climate change, on the one hand, and its readiness to improve resilience, on the other hand. The more vulnerable a country is to climate change, the lower its score; the more ready a country is to improve its resilience, the higher its score. Dominica has a low vulnerability score and A high readiness score (Table 2). The 2022 ND-GAIN Country Index ranked Dominica

67th out of 187 countries most vulnerable to climate change and the 51st most ready country to implement climate resilience solutions, resulting in an overall world rank at 69th position. On this basis, Dominica ranked 4th out of 13 Caribbean SIDSs, suggesting that it is very well positioned to support its climate resilience strategy.

Table 2. Caribbean SIDSs: ND-GAIN 2022 country rankings (out of 187 countries).

Country	Vulnerability	Readiness	Overall World Rank
Barbados	128	29	30
Grenada	115	43	46
St. Lucia	122	75	63
Dominica	67	51	69
St. Vincent and the Grenadines	80	60	71
Jamaica	94	96	88
Antigua and Barbuda	61	78	90
The Bahamas	72	92	97
Trinidad and Tobago	125	135	100
Suriname	92	141	112
Guyana	83	131	112
Belize	64	138	120
Haiti	43	187	177

Note: St. Kitts and Nevis is not part of the ND-Gain Country Index. Source: Author's compilation based on data from University of Notre Dame (2022).

In this respect, Dominica has developed ambitious mitigation and adaptation policies to further its climate resilience vision. Dominica's mitigation policy seeks to transition to 100 percent renewable energy by 2030, mainly using its vast geothermal resources as a development pathway to the green hydrogen (H2) market. Green H2 is a critical enabler to decarbonize carbon-intensive industries in the world's transition to net-zero, and it can play a key role in helping Dominica to export green energy to neighbouring Caribbean countries (KGL 2022). In late 2024, the Geothermal Power Company of Dominica borrowed USD 35 million from the Caribbean Development Bank to fund the construction of a new geothermal power plant in the Roseau Valley. The project is designed to strengthen Dominica's energy security, reduce electricity production costs, and significantly lower carbon emissions in the power sector (CDB 2024). In its updated 2022 Nationally Determined Contribution (NDC), Dominica

has set the most ambitious target to reduce greenhouse gas (GHG) emissions in the Caribbean of 45 percent below the 2014 baseline by 2030 (GoCD 2022). For this reason, Dominica's NDC is conditional on the receipt of timely access to international climate financing.

Dominica's adaptation activities seek to reduce the country's vulnerability to climate risks while promoting sustainable development. Priority areas for adaptation include substantial investments in food security, climate-smart agriculture, climate-proof tourism, health, coastal zone property management, and infrastructure development, while special consideration is given to vulnerable groups such as low-income populations, disabled or elderly individuals, and the indigenous Kalinago community, as well as to gender disparities. These adaptation investments are estimated to cost a minimum of USD 25 million between 2015 and 2030 (GoCD 2022), or close to 5 percent of Dominica's GDP, most of which is expected to be financed by debt, further increasing the country's already onerous debt burden.

Like many other Caribbean SIDSs, Dominica is caught in a middle-income country debt–climate change trap (Rambarran et al. 2024). Beyond direct impacts, the 14 tropical storms and hurricanes that have hit Dominica over the past sixty years have shocked the country's public finances and undermined its debt sustainability (Rasmussen 2004; World Bank 2011). While international aid flows helped to mitigate some of the immediate effects of these disasters, the amounts received or pledged fell far short of what was required for reconstruction and were not promptly available (Melecky and Raddatz 2011). Due to limited fiscal resources and the fragile state of public finances prior to these disasters, Dominica has little choice but to resort to borrowing to complement the amounts received from international aid in order to undertake the required rehabilitation and reconstruction of destroyed capital infrastructure.

As a result, the financial resources that Dominica needs to invest in climate resilience are increasingly being diverted to debt repayments, while rising borrowing costs, partly due to climate shocks, lead to further debt accumulation. Sahay (2005) and Greenidge et al. (2012) find that public debt above a threshold of 60 percent of GDP is considered detrimental to growth and sustainable development. At the end of 2023, Dominica's public debt stood at over 97 percent of GDP (see Table 3), which suggests that the country is well beyond the level of sustainability. As public debt has expanded, Dominica's debt service payments have almost doubled to 20 percent of total revenue in 2023, up from five years ago. Increasing debt service is limiting funds to support climate investment, heightening the small island's vulnerability to climate risks. Although, by 2024, real GDP growth in Dominica had returned to

pre-pandemic levels due to the construction of climate-resilient infrastructure and new hotels and a rebound in tourism (IMF 2024), fiscal and external imbalances remain large.

Table 3. Dominica: selected economic indicators, 2019–2023.

Selected Economic Indicators	2019	2020	2021	2022	2023
Real GDP growth (percentage change)	5.5	−16.6	6.9	5.6	4.7
Fiscal balance (% of GDP)	−8.6	−7.5	−8.2	−7.2	−3.8
Debt service (% of tax revenue)	10.2	9.1	11.7	12.9	19.2
Gross public debt (% of GDP)	97.7	112.5	108.5	103.3	97.5
Fuel imports (% of GDP)	4.9	6.5	8.2	8.6	8.2
Current account balance (% of GDP)	−38.1	−37.4	−32.9	−26.7	−33.7

Source: Author's compilation based on data from IMF (2024).

3. Proposed Climate Financing Strategies

A successful implementation of Dominica's climate resilience strategy depends on the government's capacity to mobilise mainly concessional climate finance resources, as well as its ability to use those resources effectively and efficiently. This comes on top of the existing need for development financing, particularly to meet the other Sustainable Development Goals (SDGs). Since Dominica does not have access to international capital markets, it relies mainly on capital inflows from its CBI programme and marginal grants and concessionary loans from international development partners to fund its climate change objectives. However, most of these traditional external financing flows are likely to face challenges over the medium term, possibly impacting the funding and implementation of Dominica's climate resilience vision. Dominica urgently requires novel financial solutions that not only meet the challenge of climate change but also move the country closer towards achieving longer-term debt sustainability. Some financing mechanisms which the Dominican Government can consider include those described in more detail below.

3.1. Debt Pause Clauses

A shortcoming of the global financial system is the absence of a comprehensive and consistently applied mechanism to suspend debt payments when a country is hit by an extreme climate event. This means that, in many cases, countries must continue servicing their debt when a climate extreme event strikes, diverting vital resources away from emergency response efforts. Antigua and Barbuda, for example, had to

make a USD 3 million debt payment to the IMF one day after Hurricane Irma nearly completely wiped out Antigua's smaller, sister island of Barbuda to the tune of USD 152 million in loss and damage (Courthouse News Service 2017). Climate-resilient debt clauses (CRDCs) have been proposed as one tool to address the issue of debt suspension when a country is hit by a climate shock.

In a Centre for Disaster Protection study on innovations in sovereign debt, Mustapha et al. (2023) argues that a CRDC—also known as a debt pause clause, or a natural disaster clause—would allow a government to temporarily defer debt repayments (principal and/or interest) to creditors for a pre-agreed period when a pre-defined trigger threshold is met after the passage of a natural hazard event such as a hurricane. The debt pause clause does not provide new financing to the government, but it provides breathing space for the government to redirect financial resources towards critical areas such as response and recovery efforts in the aftermath of a natural disaster instead of making debt payments. CRDCs, however, do have limitations. They may lead to increased debt servicing costs in the long run due to the combination of accumulated interest and extended repayment periods. In addition, private creditors may be discouraged from lending to countries with debt pause clauses in their debt contracts or may simply raise the credit risk premium to compensate for the possibility of future suspension of debt service repayments.

During its second debt restructuring in 2015, Grenada became the first country in the world to include a 'hurricane clause' in bond contracts with its 2025 Eurobond creditors and with its bilateral creditors of Taiwan, Province of China, and the Paris Club. Following the impact of a hurricane, Grenada would be able to activate the hurricane clause which would automatically reprofile its debt service (Asonuma et al. 2018). In July 2024, Hurricane Beryl, an early-season Category 5 hurricane, caused loss and damage equivalent to 16.5 percent of GDP to Grenada's smaller northern island dependencies of Carriacou and Petite Martinique. As a result, Grenada triggered its hurricane clause with its private creditors, enabling the government to defer some USD 12 million in interest payments due to bondholders between 12 November 2024 and 12 May 2025.

At COP28, held in Dubai in 2023, the World Bank announced that it would be significantly broadening the scope of its debt pause clauses and increasing the number of eligible countries to 45 small islands and states, including Dominica. The CRDCs will cover all existing loans in eligible countries, not only new loans. In addition to principal payments, the new initiative will now allow countries to defer interest payments on new and existing loans. The fees associated with implementing debt pause clauses will be covered by concessional resources. Saint Vincent and the

Grenadines, which suffered damage estimated at around 19 percent of GDP from Hurricane Beryl, became the first Caribbean country to trigger its CRDC with the World Bank and to obtain much-needed liquidity for its response efforts.

The experiences of both Grenada and St. Vincent and the Grenadines with debt pause clauses will provide valuable lessons to Dominica when considering the possible adoption of CRDCs in its bond agreements.

Along with debt pause clauses, the Dominican authorities may also wish to investigate issuing both GDP-linked debt and longer-maturity nominal debt, as these two debt management policies can help boost their fiscal space in undertaking climate resilience projects. Kim and Ostry (2021) demonstrate that by explicitly linking debt service to repayment capacity, a GDP-linked debt contract helps not only to stabilise a country's debt ratio but also to reduce default risk, allowing the debt contract to be finalised at a lower average interest rate. In addition, longer-term maturity debt helps to boost fiscal space. Lengthening the debt's maturity reduces default risk, lowers average interest rates and enhances fiscal space. Demertzis and Zenios (2019) argue that such state-contingent debt instruments could provide market-based insurance to protect the euro area from future debt crises, a debt management policy issue that is also very relevant to the heavily indebted Caribbean region. However, as the IMF (2017a) advises careful instrument design, robust institutions, contracts, and regulations would be needed to address the barriers to market development of state-contingent debt instruments.

3.2. Parametric Insurance for Sovereign Debt

A major drawback of debt pause clauses is that when the natural disaster strikes, the debt servicing that remains keeps getting accumulated for a later period, and this can even lead to a possible credit rating downgrade for the debtor country. In a study conducted for the International Institute for Environment and Development (IIED) on the need for a new financial compact for SIDSs, Bharadwaj et al. (2023) states that parametric insurance for sovereign debt can help to offset this main disadvantage of debt pause clauses. Parametric insurance for sovereign debt provides a predictable and quick source of funding to countries in the event of a natural disaster, allowing the authorities to cover their debt servicing costs while giving them sufficient time to focus on relief and recovery efforts. From an investor perspective, parametric insurance for a debtor country's sovereign debt can provide a measure of stability and certainty, making lending to the debtor country more attractive. However, the premium costs for such parametric insurance may be relatively high, especially for countries with higher credit risks. As with all parametric insurance, the effectiveness

of these instruments depends on accurate and reliable data to define triggers and thresholds for insurance payouts.

Following the devastation which Hurricane Ivan caused across the Caribbean in 2004, the World Bank helped to establish the Caribbean Catastrophe Risk Insurance Facility (CCRIF) in 2007. The CCRIF is the world's first multicounty parametric insurance pool that provides affordable insurance coverage to governments for tropical cyclones, earthquakes, and excess rainfall, with payouts made within 14 days of an event (CCRIF SPC 2023). Dominica's experience with the CRRIF is instructive of the role of parametric insurance for sovereign debt. Tropical Storm Erika and Hurricane Maria together caused combined damage to Dominica of almost USD 2 billion. Table 4 shows that Dominica received almost USD 23 million in combined payouts from the CCRIF to help with the impact of Tropical Storm Erika and Hurricane Maria, but the payout was just a mere fraction of the damage caused by these two climate-related disasters. Although the CCRIF's parametric insurance coverage could not fully cover the extensive damage from these two major hurricanes, it was able to provide a reliable source of liquidity funding to cover some of Dominica's sovereign debt service payments coming due in the aftermath of the climate events.

Table 4. CCRIF payouts to Dominica, 2015–2017.

Date	Event	Payout (USD)
August 2015	Excess Rainfall	USD 2,402,153
September 2017	Tropical Cyclone	USD 19,294,800
September 2017	Excess Rainfall	USD 1,054,022

Source: Author's compilation based on data from CCRIF SPC (2023).

This suggests there is an opportunity for Caribbean governments, including Dominica, to strengthen the CCRIF's regional risk carrying capacity. Specifically, this can include expanding the parametric insurance coverage of the CRRIF and the creation of a reinsurance facility of sovereign catastrophe regional risk insurance pools to bring down the high cost of reinsurance for Caribbean SIDSs.

3.3. Sovereign Debt Restructuring

Sovereign debt restructuring modifies the terms and conditions of a debtor country's existing debt without necessarily reducing the overall amount it owes to creditors. This process aims to provide immediate debt relief by extending maturity dates, reducing interest rates, or restructuring payment schedules, allowing for more

manageable debt servicing and creating space for the implementation of long-term recovery and development plans. Nevertheless, sovereign debt restructuring episodes have led to credit rating downgrades and increased borrowing costs over the medium term. In a Peterson Institute for International Economics (PIIE) working paper on lessons from four decades of restructuring sovereign debt, Buchheit et al. (2019) argue that debt restructuring is a complex, lengthy, and arduous process of negotiations with creditors which can severely challenge the capacities of many debtor countries. In many cases, debtor countries can end up with final restructuring agreements that involve conditionalities imposed by powerful creditors such as the IMF or private bondholders.

Over the past 25 years, Dominica and several other Caribbean SIDSs have initiated sovereign debt-restructuring operations, but their experience has been one of 'too little, too late' rather than 'too much, too soon' (Borensztein and Panizza 2009). As a result, these Caribbean nations have not been able to lock in the durable gains of debt relief, leading to repeated restructuring in a few countries, while others, such as Dominica, remain highly indebted. Between 2000 and 2024, there were 19 episodes of sovereign debt-restructuring operations in eight Caribbean SIDS—Antigua and Barbuda, Barbados, Belize, Dominica, Grenada, Jamaica, St. Kitts and Nevis, and Suriname. In 2001, Dominica restructured USD 144 million of its private external debt in a process that took 15 months to complete. Although its private creditors accepted a substantial 54 percent haircut on the debt, Dominica's experience is like that of many other Caribbean SIDSs, and it remains heavily indebted.

Dominica has demonstrated an unhealthy reliance on external borrowing, which more than doubled from around USD 185 million in 2000 to over USD 400 million in 2022. The International Development Association (IDA), the soft lending arm of the World Bank Group, is Dominica's largest creditor, holding almost 40 percent of the total external public debt stock and more than half of the country's multilateral debt (see Table 5). The IDA has been providing significantly large, highly concessional flows to Dominica in the aftermath of Hurricane Maria. Over the past two decades, Dominica turned away from borrowing from traditional members of the Paris Club[2] to non-traditional bilateral lenders, especially China, which is now its largest bilateral creditor. In addition, Dominica has borrowed from regional commercial banks, insurance companies, and even some private individuals; these loans account for

[2] Traditionally, the Paris Club has represented an informal group through which developing country governments could renegotiate a rescheduling (not reduction) of their official bilateral debt with some of their most important official creditors.

more than one-tenth of total external debt. This diversity in Dominica's debt profile complicates any attempt to restructure the country's high debt.

Table 5. Dominica: composition of external debt, FY 2022/2023.

Composition of External Debt	USD, million
Total External Debt	**378.4**
Multilateral Debt	**287.4**
International Development Association (IDA)	150.2
Caribbean Development Bank (CDB)	102.1
International Monetary Fund (IMF)	17.8
Organisation of Petroleum Exporting Countries (OPEC)	10.0
Société General	4.3
European Investment Bank (EIB)	1.4
Other	1.6
Bilateral Debt	**49.4**
Non-Paris Club	36.7
China	21.9
Barbados	5.0
Trinidad and Tobago	3.7
Others	6.1
Paris Club	12.7
Private Commercial Debt	**41.6**
Other	28.4
Commercial Banks	13.2

Source: Author's compilation based on data from GoCD (2024b).

Any new sovereign debt restructuring strategy for Dominica must take into the diversity of its public debt profile and its previous experience with restructuring private debt. Most importantly, it must recognise the growing influence of China, which has tended to pursue ad hoc debt restructurings, with varying degrees of coordination between the Chinese government and the international community and among its own lending institutions (Bon and Chen 2020). Dominica's growing indebtedness to private creditors also complicates any sovereign debt-restructuring process. To restructure private debt, debtor countries are obliged to approach private

creditors on an ad hoc basis to negotiate a solution. This is a complex and difficult undertaking, since many debtor countries including Dominica just do not have the capacity to engage these often very powerful private creditors. Suriname's recently concluded sovereign debt restructuring with its bondholders provides some lessons for Dominica and other highly indebted developing countries. Fresnillo (2024) argues that Suriname's debt restructuring with bondholders stretched the country's limited technical capacity. As a result, Suriname took three years to finalise a debt deal, which includes a contingency clause linked to the country's oil extraction, which could provide higher returns to private creditors than if a restructuring was not undertaken.

3.4. Debt-for-Climate Swaps

First developed and used three decades ago, debt swaps, also known as debt-for-nature swaps or debt-for-climate swaps, are re-emerging as an innovative financing option for SIDSs to tackle the threats of debt sustainability and climate-related vulnerabilities (Volz et al. 2020; Thomas and Theokritoff 2021). In a debt swap transaction, the debtor country exchanges part of its debt with a creditor country or organisation and uses the relieved debt service payments for specific investments in environmental conservation, social protection, or other priority areas. Seychelles became the first SIDS to demonstrate how debt-for-climate swaps could help deal with unsustainable debt in climate-vulnerable countries when, in 2016, it swapped USD 20 million of its bilateral debt with Paris Club creditors in exchange for funding the creation of the second largest marine protected area in the Indian ocean (Rambarran 2018). Subsequently, Table 6 shows that other SIDSs and countries, including Belize, Barbados, Ecuador, and Gabon, have carried out debt-for-climate swaps, with various debt service reductions and conservation outcomes.

These four recent debt swaps resulted in significant debt service reductions, primarily through maturity extension and interest rate reduction, ranging from USD 40 million in Barbados to just over USD 1 billion in Ecuador. They also resulted in making almost USD 835 million in funding available for marine conservation. Despite their main advantage of helping to reduce debt service obligations, debt swaps are complex, time-consuming, and high-cost transactions. They often require significant cooperation from multiple stakeholders, especially creditors, during extensive negotiations, and even then, the amount of debt relief may be limited compared to the overall debt burden (Bharadwaj et al. 2023). Nevertheless, there is significant potential for Dominica to learn from these debt swap deals on how best to reduce its onerous debt level while funding its costly climate resilience programmes.

Table 6. Debt-for-climate swaps, 2015–2023.

Date	Seychelles February 2015	Belize November 2021	Barbados September 2022	Ecuador May 2023	Gabon August 2023
Value of Debt Swap	USD 21.6 million	USD 364 million	USD 150 million	USD 1.6 billion	USD 500 million
Creditors	Bilateral: Paris Club	Commercial: entire 'Superbond'	Domestic and Commercial	Commercial	Commercial
Debt Impact	USD 2 mn debt service reduction Debt maturity extended by 2 years	12 pp reduction in debt/GDP ratio USD 200 mn in debt service savings over 15 years Debt maturity extended by 6.5 years	USD 40 mn debt service reduction Debt maturity extended by 8 years	USD 1.126 bn debt service reduction	Extended tenor
Conservation Outcome	USD 5.6 mn over 20 years	USD 180 mn over 20 years	USD 40 mn over 15 years	USD 450 mn over 18.5 years	USD 163 mn over 15 years

Note: pp—percentage points; mn—million; bn—billion. Source: Author's compilation based on data from Rambarran et al. (2024).

Rambarran et al. (2024) demonstrates how a new generation of debt-for-renewable swaps could provide financing for Dominica's geothermal energy project, reducing the country's debt service burden and accelerating its transition to a full reliance on renewable energy. A debt-for-renewable swap could provide an opportunity for China, as Dominica's largest bilateral creditor, to continue leading the global renewables revolution. Similarly, Trinidad and Tobago, which needs to receive a stable supply of GH2 to decarbonize its petrochemical industries, is another bilateral creditor that could benefit from a debt swap with Dominica. As Dominica's largest multilateral creditor, the World Bank can provide guarantees and credit enhancements to mitigate the risks associated with debt swap transactions.

4. Conclusions

This Chapter addressed the critical research problem of assessing the financial mechanisms that Dominica could pursue to mitigate the risks associated with its climate–sovereign debt doom loop (Zenios 2022). In this context, the resources which Dominica urgently needs to invest in while becoming the first climate-resilient country in the world are increasingly being diverted to repay debts, while its borrowing costs are rising partly due to climate-related vulnerabilities, leading to the country ranking amongst the top ten most heavily indebted Small Island Developing States (SIDSs). Key findings indicate that debt pause clauses, parametric insurance for sovereign debt, sovereign debt restructuring, and debt-for-climate swaps offer some promising financial solutions, enabling Dominica to work with various stakeholders such as the IMF, World Bank, the Paris Club, China, and private creditors to ease liquidity pressures and unlock fiscal space to finance climate resilience projects.

These findings raise several implications for policymakers. First, the Dominican authorities would need to learn from the experiences of both Grenada and St. Vincent and the Grenadines with triggering debt pause clauses when considering the possible adoption of these clauses in its bond agreements. A key learning would be whether private creditors were discouraged from lending to these two countries or simply raised the credit risk premium to compensate for the possibility of future suspension of debt service repayments. Along with debt pause clauses, the Dominican authorities may also wish to investigate issuing both GDP-linked debt and longer-maturity nominal debt, since these two debt management policies can help boost their fiscal space to finance climate resilience projects (Demertzis and Zenios 2019; Kim and Ostry 2021). Second, Dominica's experience with parametric insurance for sovereign debt in the tradition of Bharadwaj et al. (2023) suggests that there is an opportunity for Caribbean governments to strengthen the CCRIF, the region's catastrophe risk pool. This could include expanding the parametric insurance coverage of the CRRIF and the creation of a reinsurance facility among other sovereign catastrophe regional risk insurance pools to bring down the high cost of reinsurance for Caribbean SIDSs. Third, in undertaking any sovereign debt restructuring exercise, the Dominican government must recognise the growing influence of China, its largest bilateral creditor, and the complexity of engaging with powerful private creditors, which can stretch its limited technical capacity (Buchheit et al. (2019). Finally, there is significant potential for Dominica to learn how a debt-for-renewable swap could reduce the country's high debt service while providing financing for its geothermal energy development (Rambarran et al. 2024).

This research acknowledges the limitations of the above financial mechanisms. Chamon et al. (2022) cautions that for countries with unsustainable debt, like Dominica, such financial instruments would not be sufficient to restore solvency but would need to part of a wider package of reform to the global debt architecture. Additionally, the challenges associated with Dominica's climate–debt nexus, like those of many other SIDSs, reflect the structural weaknesses of the global financial architecture (UNCTAD 2022). Richer developed countries have failed to meet the USD 100 billion per year which they pledged at COP15 in Copenhagen in 2009 and reaffirmed at COP21 in Paris in 2015 to assist developing countries in the fight against climate change. Apart from the volume of climate finance flowing from developed to developing countries falling short of the commitment made (Oxfam 2023), most of the funds have been delivered as loans, adding to the debt burden of already stressed countries, while the distribution of funds prioritised mitigation, left adaptation woefully underfunded (OECD 2022), and ignored loss and damage—the impacts of the climate crisis that cannot be prevented or addressed and most relevant to Caribbean countries such as Dominica. In 2024, COP29 delivered a contentious agreement on a new climate finance goal of mobilising at least USD 300 billion annually by 2035, three times the previous target, but far less than developing countries require to pursue low-carbon development. As a result, all parties are working to reach agreement in 2025 on the 'Baku to Belém Roadmap to 1.3T', which envisages scaling up climate finance to at least USD 1.3 trillion to developing countries (UNFCCC 2025).

In this regard, future research directions should focus on how the international community can improve the access of Dominica and other climate-vulnerable countries to mostly concessional long-term financing for their climate resilience strategies. Further studies examining the necessary reforms to the global financial architecture to support Dominica and other SIDSs in addressing their interlinked debt and climate financing challenges could significantly contribute to policy formation. In conclusion, mitigating risks associated with the climate–debt nexus demands immediate global attention. Proactive and strategic responses, grounded in thorough research, are essential to ensuring that high-debt, climate-vulnerable nations like Dominica are able to achieve their shared climate and sustainable development goals.

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Community-Oriented Climate Action Plan in a Mid-Sized Shoreline Municipality: A Canadian Case Study

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1. Introduction

Canada's Changing Climate Report (Bush and Lemmen 2019) highlights the urgency of responding to the climate crisis. While the federal government has made commitments through the Emergency Management Strategy, the responsibility for designing and implementing protective policies largely falls to municipalities (Cigler 1988). Since the national declaration of a climate emergency in June 2019, over 520 municipalities (representing 98% of Canada's population) have echoed this call by declaring local climate emergencies and setting Net Zero targets (Climate Emergency Declaration 2022).

Municipalities make policy decisions within the constraints of provincial legislation, balancing environmental, political, and economic pressures based on issue salience (Henstra 2010). Climate-related issues often rise on the decision agenda when supported by public opinion or lobbying efforts. In such cases, elected officials may defer to specialists and policy analysts to propose long-term strategies tailored to regional needs. Public support or opposition then provides valuable political feedback on these choices (Henstra 2010).

We use a case study of the Municipality of Port Hope as a framework for developing effective policy recommendations that supports a balance of public participation and the integration of opinion among the population in promoting issues to the top of the decision agenda. The applied framework was inspired by the model of Remedial Action Plan (RAP) initiatives involving multiple perspectives, including vision setting, community engagement, collective ownership, shared governance, joint decision making, and scalability to other communities (Krantzberg 2020).

Situated on the northern shore of Lake Ontario, about 110 km east of Toronto, on the Ganaraska River, the mid-sized Municipality of Port Hope supports a population of approximately 17,000 and approximately 279 square kilometers, the highest number per capita in Canada (Townfolio 2016). Port Hope typically experiences the

most rainfall in September, with 93mm of precipitation on average, which makes up nearly 12% of the annual rainfall (Environment Canada 2020). The region is a picturesque blend of urban and rural areas preserved as such intentionally for cultural heritage conservation. The mixed-use development in Port Hope is surrounded by farmland, the 11000-acre Ganaraska Forest, and shoreline communities around the second deepest lake within the North American Great Lakes system. As the largest group of freshwater lakes on Earth, the Great Lakes (Superior, Michigan, Erie, Huron, and Ontario) contain 21% of the world's freshwater by volume (Wuebbles et al. 2020). The Great Lakes region is one of the most valuable natural features of North America, which defines the health and lifestyle of two Canadian provinces and eight states in the United States (Hartig et al. 2019). Over the years, the basin and ecosystem of the Great Lakes have become subject to the dangers of polluted water and toxic residues, impacting the quality of life in the region, shaping a focused binational commitment to clean water on what came to be termed the Great Lakes "Areas of Concern (AOC)", beginning in 1985. Port Hope was identified as one of the Areas of Concern by the government of Canada in 1987 due to legacy contaminations and its low-level radioactive waste problems (Weston 1995).

Beginning in 2001, efforts towards remediating the area have been undertaken in partnerships between the federal and other levels of the government under the Canada–Ontario Agreement on Great Lakes Water Quality and Ecosystem Health (COA) and are mainly focused on radioactive waste management and cleanup (Government of Canada 2017). Nonetheless, monitoring activities since 1985 in all AOC have identified climate change as one of the challenges in the region (Hartig et al. 2009). The trends of increasing frequency and intensity of extreme heat and precipitation are consistent with the expected response to a warming climate that has been confirmed by multiple independent research groups around the world (Wuebbles et al. 2020). The observed and projected trends of other extreme events such as heavy storms, flooding, and drought are characterized more regionally. For instance, in 1980, the Ganaraska River spilled its banks and covered 66 acres of downtown Port Hope in 1.5 m of water (Ganaraska Region Conservation Authority 2009). As a result of more frequent storms in the Great Lakes region, the town of Cobourg, near the Municipality of Port Hope in Ontario, experienced a massive flooding event in 2010, posing severe threats to the infrastructure such as sewage systems and agricultural land erosion (Dillon 2010). Such severe storms can also cause large amounts of waste or contaminants to travel into local waterways, thereby impacting local drinking water, stormwater management, manure management systems, and vector-borne diseases (Erickson 2019).

Flooding is Canada's costliest and most frequent natural disaster (Public Safety Canada 2019). Despite the long history of floods in the area, the Municipality of Port Hope has not yet declared a state of emergency regarding the climate crisis. The threat of flooding events is significant to the agricultural economy of the region as the planting, maturing, and harvesting of crops all depend on consistent seasonal patterns (Climate Atlas of Canada 2010). Given the focus of the municipality's official plan on progressive economic growth, it is prudent for the local government to adapt to new conditions and strive to mitigate further climate crises. In order to increase the efficacy of the responses to climate change, climate change action planning must be institutionalized at all levels of society (Burch 2010) and gain legitimacy during the strategy and policy development phase (Capstick et al. 2015). Meaningful public participation and integrating local knowledge can not only contribute to obtaining societal trust (Bickel et al. 2020), but can also have a decisive impact on the success or failure of the policy in meeting its objectives (Whitmarsh et al. 2013).

Having been impacted by massive flooding events, the community of Port Hope intimately knows the adverse effects of climate change on the local infrastructure and human health, has already been heavily involved in the environmental restoration of the region, and can further contribute to the implementation stage. Lastly, in a democratic structure such as Canada, improved public involvement and individual evaluation of the proposed policy could impact the advocacy for or against the supporting political leadership (Whitmarsh et al. 2013). As such, a community-driven framework that includes all stakeholders in decision-making processes leading up to a local climate change action plan provides a well-suited approach for the Port Hope Municipality to ensure implementation projects are supported by the community at large by developing a sense of understanding of the issues and priorities of actions that, if made explicit and communicated to the municipal council, generate more ownership and responsibility amongst residents, community groups, non-profit organizations, and local businesses.

2. Materials and Methods

2.1. Community-Oriented Survey Design

After being assigned as the advisory body to the Municipal Council, the Climate Change Working Group approached the policy experts from McMaster University as the support resource in developing recommendations for driving effective local climate actions and planning efforts for long-term emergency management. A series of municipal workshops were initially designed by McMaster to discuss the risk associated with emergency inaction and encapsulate the ideas and opinions that

would help create a comprehensive report for the municipality council to rely on when recommending further mitigation and adaptation strategies to the local government. With the onset of the COVID-19 pandemic and the shift to virtual communication platforms, this approach was modified after the first workshop in October 2019 to include a series of semi-structured ethnographic interviews with acknowledged community leaders representing the residential category, activist groups, businesses (small and corporate), educational institutes, and agricultural community. Semi-structured interviews were chosen for their flexibility and depth, allowing participants to share contextual insights while still responding to a consistent set of guiding questions. Interviews focused on participants' perceptions of climate risk, barriers to local action, and priorities for adaptation. The qualitative data collected were used to shape the structure and language of the subsequent community survey.

Out of sixteen participants contacted by email to be interviewed, twelve responded positively (75% engagement rate) and received the interview questions in advance of the scheduled interview time. These interviews took place over a period of three months in 2020, and all participants were guaranteed anonymity. The questions for these interviews were open-ended and designed to determine if the respondent agrees with the concept presented in the question, followed by collecting more details to clarify the response. This method was designed specifically to discover insights and unique perspectives that later facilitated the community survey development.

As an alternative tool to in-person public engagement, the community survey was designed based on the information acquired from the initial interviews and further feedback from the Port Hope Centre of Excellence, renamed as the Climate Change Working Group, in 2021. The questions underwent a peer review process before the survey became available to the Port Hope community in April 2021 through an online survey collection tool and remained open for 30 days. The community leaders were invited to complete the online survey and distribute it amongst their network through email. The online survey was also made available and promoted through social media platforms and the central website for the Municipality of Port Hope.

2.2. Data Collection

The survey contained five sections consisting of (1) demographic data, (2) awareness and perceptions of climate change, (3) views on climate change in Port Hope from the community perspective, (4) views on climate change in Port

Hope from the local government perspective, and (5) use of social media as a source of information about climate change. In terms of demographic data, the survey was available to any respondent who either lived or worked in Port Hope or had a community or personal connection to the area.

As for the perception of climate change, some questions were presented in the form of statements. The respondent would choose the level of agreement; other questions were more open-ended, providing the responder with an option to type in their own opinion in addition to those offered by the survey. With respect to expectations from the local government, the respondents were asked to rank the actions identified as necessary by the community leaders as high-, medium-, or low-priority. In addition to a total of 35 directed questions, the respondents were given an opportunity to share their comments in a final free-text question prior to submitting their answers. All responses were collected by the online platform and extracted once the survey was closed to the public.

2.3. Measure

Given the sample size, we aimed for a confidence level of ninety-five percent. With a population of 16,755 in the Port Hope Municipality, we expected to collect about 1000 responses to achieve the initial goal. Out of the total target population, only 199 completed the community survey, providing us with a $\pm$7% margin of error using the following formulas:

$$n = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + (\frac{z^2 \times p(1-p)}{Ne^2})} \text{ and } e = z \times \frac{\sigma}{\sqrt{n}}$$

where e is the error margin, σ is the population standard deviation, n is the sample size, N is the population size, and the value for z is assigned based on the desired confidence level. Based on the 95% desired confidence level, we assigned a value of 1.96 to z. This means that we are ninety-five percent confident that the obtained result from this survey does not differ from the attitudes of the whole target population by more than $\pm$7%.

The submitted responses were extracted and uniformed by the research team after the survey was closed to the public. Any question left blank by the respondent was not included in the data analysis. The data analyzed are provided in five sections: one is the overall outcome analysis of all respondents, and the remaining four are separate comparative analyses based on the education level, income level, area of living (urban or rural), and age group of the participants.

While the survey was not formally pre-tested, the questions underwent internal peer review to ensure clarity and relevance. The online tool used for distribution did not include IP-based filtering or CAPTCHA protections, so we cannot fully rule out duplicate entries, though no patterns suggested artificial inflation. All incomplete responses and blanks were excluded from the analysis, and "prefer not to say" entries were removed in subgroup comparisons. These steps aimed to maintain data integrity while recognizing the limitations inherent in rapid, community-deployed surveys.

2.4. Comparing Demographic Data for Representation Based on the Census Expectations

A preliminary analysis was performed to obtain an overall census of the survey respondents. Through this analysis, we observed the distribution of respondents across all employment sectors but only considered the ones with three or more individuals, which made up approximately 89% of all respondents. To examine the role of education, we asked respondents to provide us with the level of education the respondent has completed to date, with available options listed as (a) high school, (b) college certificate, diploma, or degree, (c) bachelor's degree, (d) master's degree, (e) professional degree, and (f) doctorate based on the Canadian education system. Even though climate change is not uniformly taught across all Canadian schools (Field et al. 2019), for the purpose of our analysis, we assume all survey participants, regardless of the province or territory of acquired education, had been exposed to the basics of climate change concepts. Considering that the college curriculum is compact and mainly field-focused in Canada, we did not expect extensive exposure to climate change-specific education as part of this group of credentials. While a professional degree is also awarded in specific fields of work, they are often exclusive to either graduate or undergraduate entry, depending on the profession. We therefore assumed that the participants who indicated "professional degree" as their highest level of education had already fulfilled either a bachelor's or a master's degree requirements. Given the distribution of our participants, this comparative analysis was performed in two main categories of Non-university Education and University Education.

The survey respondents were asked to identify the household income bracket they belonged to, with options provided as under CAD 20k, CAD 20k to CAD 40k, CAD 40k to CAD 60k, CAD 60k to CAD 80k, CAD 80k to CAD 100k, and CAD 100k and over. The option of "Prefer not to say" was also provided to facilitate respondents who wished not to disclose this information. For the purpose of the study, 21.6% of the respondents who preferred not to disclose their income were excluded from further analysis. The remaining respondents were categorized based

on the income brackets set using the low-income cut-off (LICO) values provided by Statistics Canada (Statistics Canada 2021). The average family size was adopted as 3, which is representative of the Canadian national and provincial average of 2.9 for Ontario (Statistics Canada 2021). The LICO for 2019 suggested the low-income threshold for a family of 3 living in a community of under 30,000 is set as CAD 31,673 (Statistics Canada 2021). Considering the upper-bracket population of 17,000 in Port Hope, these thresholds can be adopted to define brackets for low-income households. Based upon these criteria, the respondents were categorized into three categories: under CAD 40,000 (low-income households), between CAD 40,000 and CAD 100,000 (middle-income households), and CAD 100,000 or higher (high-income households).

The data were also validated against responses to a question identifying the age group of the respondent by choosing from the following cohorts: under 16 years old, 16 to 25 years old, 26 to 49 years old, 50 to 65 years old, 66 years or older, and prefer not to answer. Due to the limited sample size, we grouped these six groups into two categories of "49 and under" and "50 and above". Those who preferred not to answer were excluded from the survey.

The County of Northumberland, and the Port Hope area specifically, contain significant rural populations, as 80% of their land area is made up of rural spaces and farmland (Northumberland County 2014). In addition, it is predicted that approximately 20% of the County of Northumberland's growth will take place in rural areas (Northumberland County 2014). Notably, the agricultural sector represented by the rural residents is significant in the economy of the region. It is therefore crucial that we understand the perspective of this demographic regarding the issues posed by climate change and the potential actions that could be taken by local governments. As such, this analysis focused on comparing the opinions of respondents residing in rural areas of Port Hope with those of the urban respondents. Retirees are slightly overrepresented in our survey results. Nonetheless, we have accepted the resulting bias in the analysis of the overall findings for recommending engagement initiatives on the basis of the cohort's higher involvement in civic engagement or volunteering compared to working populations (van den Bogaard et al. 2014). Educational attainment data in this study reflect self-reported values from survey participants; no respondents reported education below high school level.

Finally, five separate reports were designed to summarize the findings of the above analyses to serve as inputs to further strategic planning at the local government level by highlighting the disparity in community opinions about roles and responsibilities in combating the climate change impacts within Port Hope.

Due to the 7% margin of error, any disparity less than 10% was ignored in the comparative analysis.

3. Results and Discussion

3.1. Overall Findings

The Port Hope community is statistically considered above the low-income cut-off specified in Canada, with the majority of the working age group between 15 and 64 years old, and a median age of 51 (Townfolio 2016). The majority of the population have completed a high school education, and most are actively practicing engineering, business, management, and public administration (Townfolio 2016). Overall, the demographics in survey representation are fairly consistent with statistical demographics of the Municipality of Port Hope in terms of education and household income category. The majority of the respondents are over 66 years of age (37%), but there is a good percentage of representation from age groups of 26 to 49 and 50 to 65 years old (28% and 32 percent, respectively). This study observed that a vast majority of the Port Hope survey respondents consider climate change to be anthropogenic (Figure 1), identifying human activities such as deforestation and the use of fossil fuels as the top causes of climate change. Consumer behavior is considered the leading factor contributing to climate change, with energy demand, population control, and transportation. Port Hope residents also identify an increase in the frequency of extreme weather events and other financial implications as negative impacts of climate change. This strong agreement about the causes of climate change and their subsequent effects on the community indicates that Port Hope residents are well informed about the issue and in agreement about individual responsibility towards climate actions.

Evaluating the current situation, the respondents mostly believe that climate change is inevitable, and mitigating actions alone cannot sufficiently address the ongoing and potential damages. It is recognized that there is a need for a compelling set of adaptive measures. At a remarkably higher rate than that identified nationwide, the Port Hope community recognizes the role of individual responsibility in combating climate change (McLeod Macey 2020). This level of awareness within the community (Figure 2) indicates that future environmental plans in Port Hope are likely to benefit from the support and involvement of a relatively mature populace. Specifically, the Port Hope representative residents are generally willing to shift to eco-friendly products and services even if it costs more. This means that the strategic planning can count on the popularity of actions that require a reasonably higher willingness to pay to combat the negative impacts of climate change and reduce

GHG emissions. The emphasis on individual responsibility and consumer behavior is an indication that the community will receive these types of elements well within a potential municipal Climate Change Action Plan.

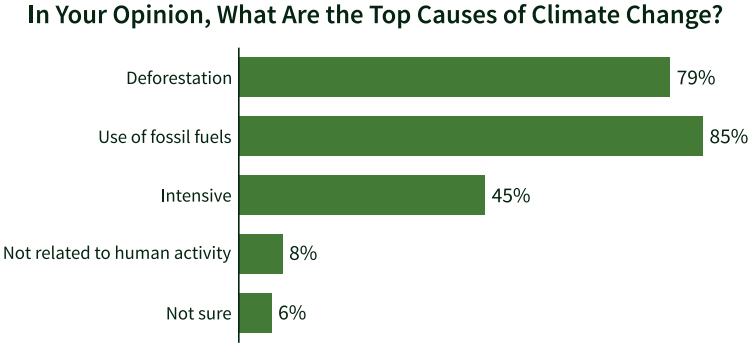


Figure 1. Top causes of climate change as identified by survey participants. Source: Figure by authors.

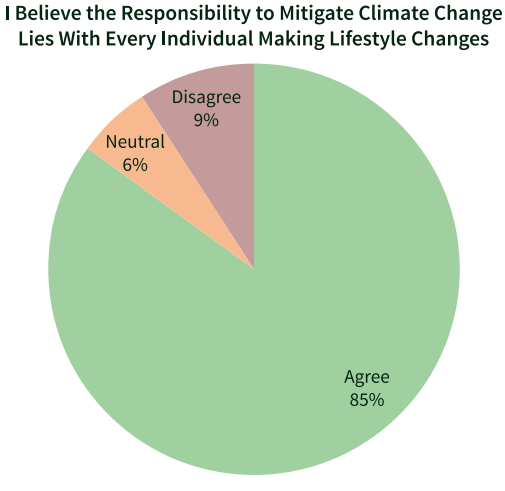
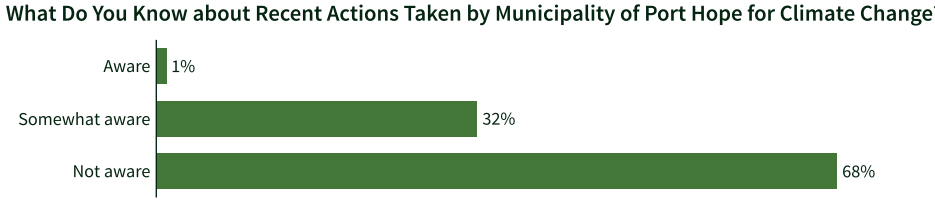


Figure 2. Survey participants' attitude towards individual responsibility in tackling the climate crisis. Source: Figure by authors.

Even though a vast majority of the respondents follow at least one form of Port Hope-related content on social media, only a small proportion of respondents express high awareness about the activities the municipality has undertaken toward combating climate change (Figure 3). This signals low awareness regarding local climate initiatives in Port Hope and that there is a need for more awareness initiatives

on the part of the municipality. This will be especially important to address as climate action awareness is a key indicator for climate change initiative engagement (Mavrodieva et al. 2019). This matter can result in a low level of public trust and involvement in the municipality's existing and future plans.

Potential robust public outreach for the municipality can inform, engage, and consult the local people in planning future climate actions to leverage public engagement during implementation. The co-benefit of this plan is the promotion of reliable and scientific information and prevention of widespread misconceptions through social media channels. Further, since social media (Figure 4) has been identified as one of the most popular means of communication in Port Hope, it is vital to consolidate the platforms run by the municipality to improve coherence in communication and keep the entire community equally informed.



List of actions taken by the municipality is provided in the survey as below:

- Engaging local citizens and organizations around the issue of climate change
- Working collaboratively with the wider community to develop local solutions to climate change
- Reaching out to higher levels of government for assistance related to climate change
- Funding of specific projects/programs (mitigation/adaptation) intended to help address climate change in Port Hope
- Reporting on Port Hope's progress to address climate change
- Modelling 'climate leadership' in the design, delivery and monitoring of local municipal services

Figure 3. Participants' knowledge of recent actions taken by the municipality for the climate crisis. Source: Figure by authors.

There is a slight disparity among respondents' judgment of the performance of private and public sectors in addressing climate change. Respondents believe that both these sectors have had an unsatisfying performance in either adopting practical strategies or effectively communicating actions and plans to people, leading to a notable lack of information about their activities. More than eighty percent of respondents believe that the government should incentivize private companies to reduce their emissions (Figure 5). The level of public dissatisfaction can be considered a benchmark for the decision makers to evaluate the success and effectiveness of their future plans, provided increased private sector engagement and the use of external expertise (Dannevig et al. 2012).

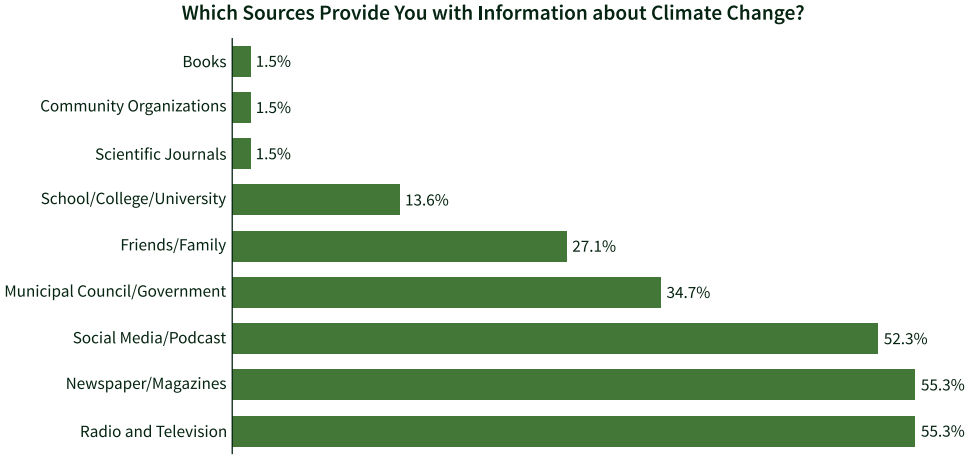


Figure 4. Survey participants' sources of climate change information. Source: Figure by authors.

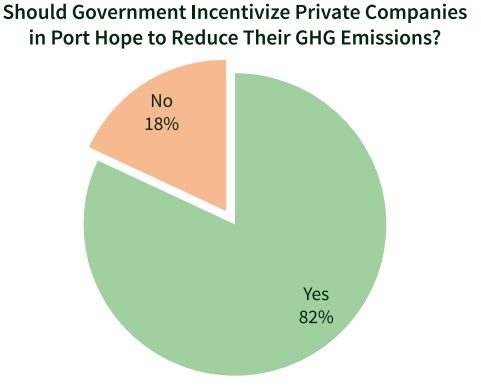


Figure 5. Survey participants' opinion on incentivizing GHG reduction for private companies by the government. Source: Figure by authors.

Given the growing importance of climate change, municipal government support for the agricultural community as well as affordable housing for the existing population are of the utmost priority for the participants in this study (Figure 6). Governmental supports have always played a crucial role in stabilizing the agricultural economy, reducing the potential outcomes of uncertain risks including harsh weather conditions or pests, and providing farmland protection (Eagle et al. 2016). Based on this survey, acknowledging and prioritizing matters pertaining to anthropogenic climate change and increased support for the vulnerable populations take precedence over local economic development, job creation, quality

of life improvements, First Nations reconciliations, municipal upgrades, and tax increases. It is worthwhile noting that below 2% of the Port Hope population identify as Aboriginal, out of which 60% are from the First Nations (Townfolio 2016).

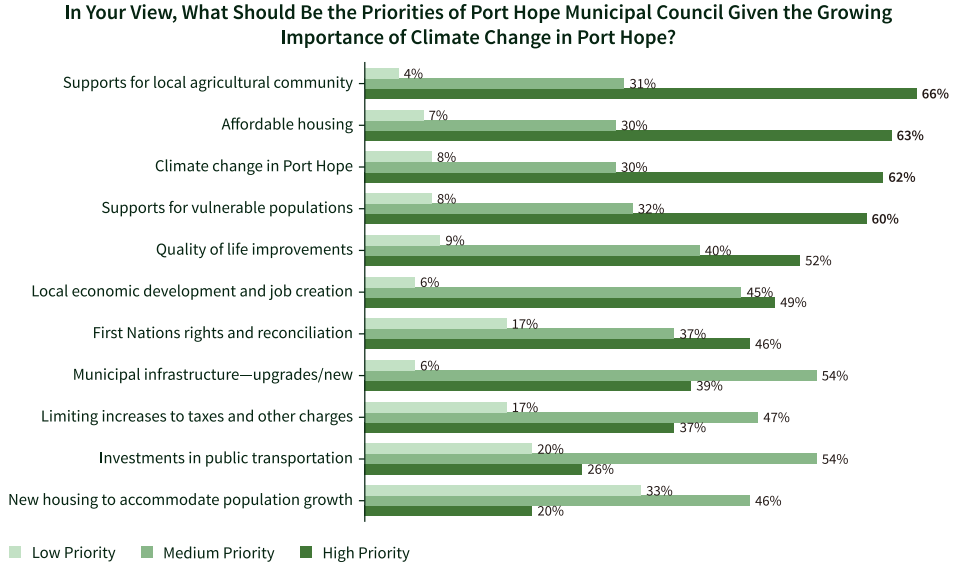


Figure 6. Survey participants' assessment of priorities for Port Hope Municipal Council. Source: Figure by authors.

In addition, it is evident that the Port Hope survey respondents have ascertained opinions and consensus on several areas of focus within local climate action. For example, there is a broad consensus among respondents in Port Hope regarding decarbonization of municipal infrastructure. Similarly, Electric Vehicles (EVs) are determined to be the most attractive type of transportation (Figure 7).

Further, respondents expect the municipality to collaborate with all levels of government to secure funding for climate change mitigation; about eighty percent of respondents advocate for adaptative plans that involve tree planting and saving Ganaraska watershed wetlands, as well as mitigative actions such as expanding the local tree canopy (Figure 8). This means that institutions or individuals responsible for taking actions and making decisions regarding environmental issues should address and prioritize the same concerns as the respondents unanimously do. A different set of strategies requires a comprehensive rationale for convincing the public about the validity of the decision.

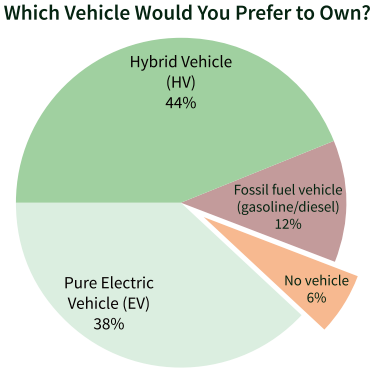


Figure 7. Survey participants' vehicle preference. Source: Figure by authors.

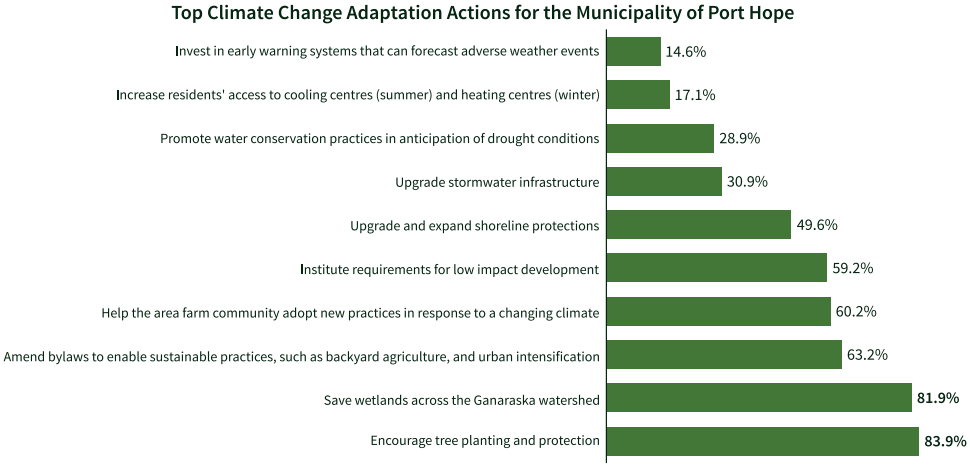


Figure 8. Survey participants' view on top climate change adaptation actions for the Municipality of Port Hope. Source: Figure by authors.

3.2. Education

Our findings from the education-based comparative analysis help understand the dominant and divergent perspectives of Port Hope's citizens on the climate crisis based on their level of education. According to the Intergovernmental Panel on Climate Change, there is a consensus among the scientific community on anthropogenic climate change (IPCC 2014). In other words, scientific evidence is "virtually certain" (suggests a 99–100% confidence) that changes in extreme weather conditions and climate events have been caused by human influence on greenhouse gas emissions (IPCC 2021). In this regard, by assuming anthropogenic climate change as a scientifically proven fact, we can intuitively expect that as the

level of education rises, greater confidence in climate change as human-caused is observed. This intuition also has been confirmed by several empirical surveys (Arbuthnot 1977; Buttel and Johnson 1977; Maloney and Ward 1973; Poortinga et al. 2019; Sun and Han 2018). The mentioned trend, however, is not what the Port Hope survey result suggests. A vast majority of our respondents, regardless of their highest level of education, acknowledged anthropogenic climate change and counted deforestation and humanity's use of fossil fuels as the top causes of climate change (Figure 9). University-level education does not seem to play a determinant role in the confirmation or rejection of human-caused climate change.

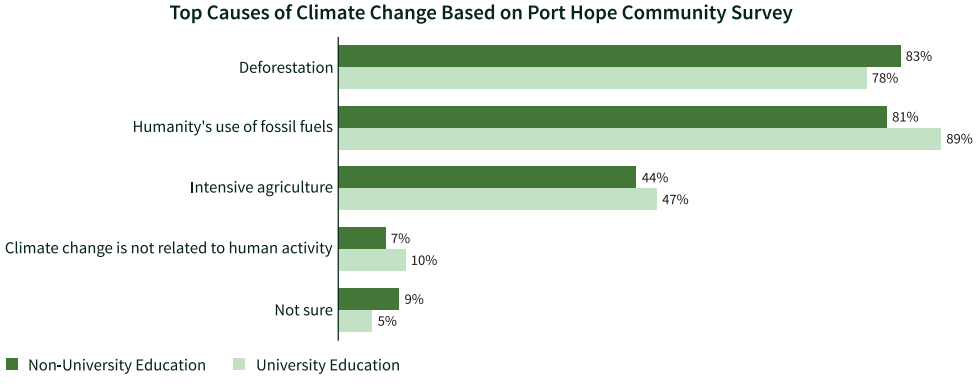


Figure 9. Distribution of survey participants' opinion on top causes of climate change based on educational attainment. Source: Figure by author.

Regarding the perception of our respondents about their individual responsibility in the context of climate change, the university degree holders, to a lesser extent, agreed to revise their lifestyle in combating climate change. Moreover, in terms of their environmental attitude, university degree holders generally seemed to be less optimistic about actions to mitigate climate change (Figure 10) and showed a lower level of agreement on individual responsibility as an indicator for this belief. The majority of respondents in this group rated the climate-related performance of the public sector poor, more so than the private sector. It could be anticipated that municipal authorities could face intense challenges if they particularly count on highly educated citizens' environmental behavior.

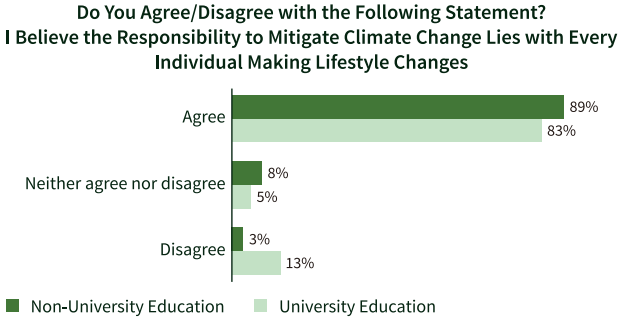


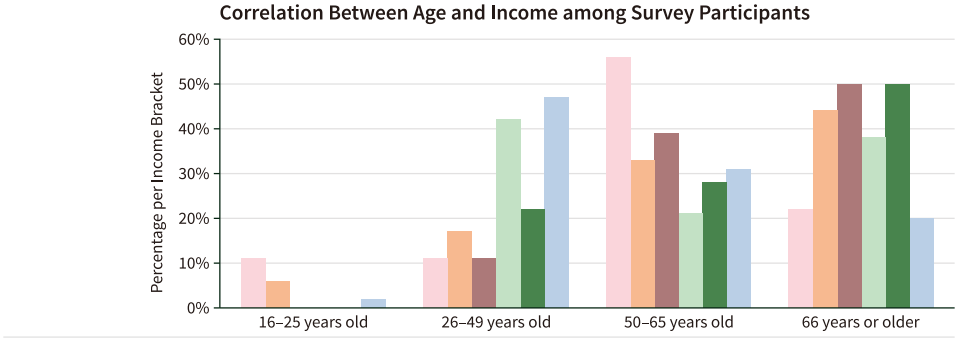
Figure 10. Distribution of survey participants' opinion on individual responsibility to mitigate climate change based on educational attainment. Source: Figure by authors.

3.3. Income

In the analysis of this community survey, the low-income respondents are significantly underrepresented, whereas the representation of middle-income and high-income is two and three times higher, respectively. This study suggests that low-income participants are more likely to actively follow climate change news and align with the causes and consequences of climate change than other income levels. Notably, the majority of our low-income participants were between 50 and 65 years of age (Figure 11). Studies show a positive correlation between perceptions of the importance of climate change and economic well-being (Lo and Chow 2015; Poortinga et al. 2019). Income levels are also related to vulnerability. Especially in the context of floods, per capita income has its most prominent effect on reducing the likelihood of a flood (Kahn 2005). In one study, income directly correlates with a variety of vulnerability factors, suggesting that vulnerability increases with a decrease in income (Deria et al. 2020).

Our analysis revealed a wide array of trends. Some trends were in line with the existing literature, while others slightly deviated. For instance, previous studies on the relationship between environmental purchases and income suggest a positive correlation. An increase in income positively affects environmental purchasing (Bülbül et al. 2020; Çabuk et al. 2008). Overall, a greater proportion of Port Hope residents think of eco-friendly products as expensive (Figure 12).

The findings from the survey revealed that all income groups in Port Hope, including the lower-income households, expressed an equal inclination toward electric and hybrid cars. These findings are slightly in contrast with what is suggested in the literature. For instance, a study in Europe indicates that higher-income groups are more likely to adopt them due to the relatively high upfront cost of electric vehicles and hybrid vehicles (Zubaryeva et al. 2012).



	16–25 years old	26–49 years old	50–65 years old	66 years or older
Under CAD 20,000	11%	11%	56%	22%
CAD 20,001 to CAD 40,000	6%	17%	33%	44%
CAD 40,001 to CAD 60,000	0%	11%	39%	50%
CAD 60,001 to CAD 80,000	0%	42%	21%	38%
CAD 80,001 to CAD 100,000	0%	22%	28%	50%
CAD 100,001 or over	2%	47%	31%	20%

Figure 11. Correlation between age and income among survey participants. Source: Figure by authors.

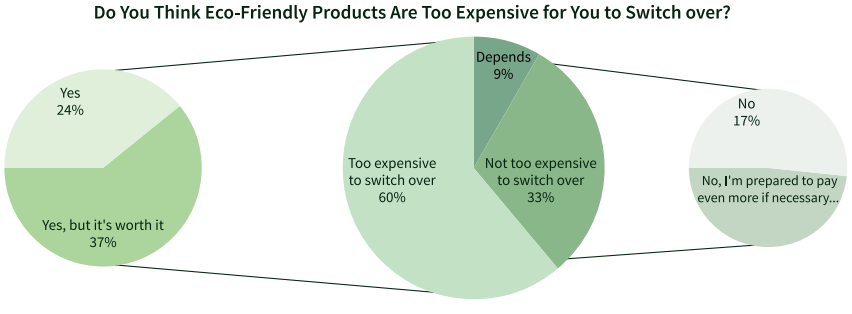


Figure 12. Survey participants' opinion on affordability of eco-friendly products. Source: Figure by authors.

In the case of identifying responsibility towards climate change, income acts as a constraint on individual responsibility during times of financial recession. However, it is less influential under better economic conditions (Eden 1993). The Port Hope community has a median income of CAD 72,435, on par with the national average (Townfolio 2016). As such, it is not surprising that even low-income households are pro individual responsibility. However, the much higher skepticism among individuals from high-income households can be associated with the perceived inefficiency of individual responsibility in addressing climate change and identification of other stakeholders (governments, cooperates, municipalities, etc.) to take up the task (Eden 1993).

3.4. Age

There are noteworthy trends between age and diverging perspectives on specific issues presented in the survey. The literature indicates that younger people are likely to possess a higher level of environmental knowledge than older people (Diamantopoulos et al. 2003; Jain and Kaur 2004). Younger people are more vulnerable; they face the consequences of climate change legislation being constructed by the preceding generation and are simultaneously tasked with stipulating societal responses to climate change (Corner et al. 2015). Despite not entirely trusting the governments, the younger population holds them accountable for devising climate change action plans (Corner et al. 2015).

The second notable trend in the literature is the correlation between age and awareness about environmental issues. For instance, according to one study environmental consciousness among survey participants in the age bracket of the 40s to 60s is higher compared to that of younger people (Morrison and Beer 2017). Corner et al. (2015) also confirm this in their results, highlighting a lower technical understanding among the younger age cohort about the factors causing climate change. Meanwhile, Wells et al. (2011) found that General Environmental Responsiveness (GER), which is a score used to evaluate performance associated with climate change, increases in accordance with age. Furthermore, a study in 2004 demonstrated that among participants between the ages of 41 and 60 years, the majority identified climate change as an important concern, suggesting that this age cohort was better equipped for risk assessment in comparison to the younger age group (Stedman et al. 2004).

Our findings show notable correlations between age and differing perspectives on specific issues, but they are not uniformly distributed among all topics. The divergence of opinion mainly manifests in the performance of the public transportation system (Figure 13) and First Nations rights and reconciliation. Overall, the community representation of the under 49 years of age group leans towards a collectivist perspective, while the over 50 years old group demonstrates a slightly more individualistic view regarding how they perceive climate change and the potential actions to combat these issues. This aligns with research suggesting that environmental skepticism regarding climate issues is more pronounced in the older population compared to the youth (Wang and Kim 2018; Zhou 2015). Furthermore, significant differences are also noted in the impact of social media section, illustrating that those who are 49 or under are active participants on social media platforms and therefore view climate change-related information more frequently on such platforms than the group of 50 and over. These findings indicate that with the exception of the

aforementioned disparities, the actions taken by the Port Hope Municipality will be perceived somewhat similarly among all age cohorts.

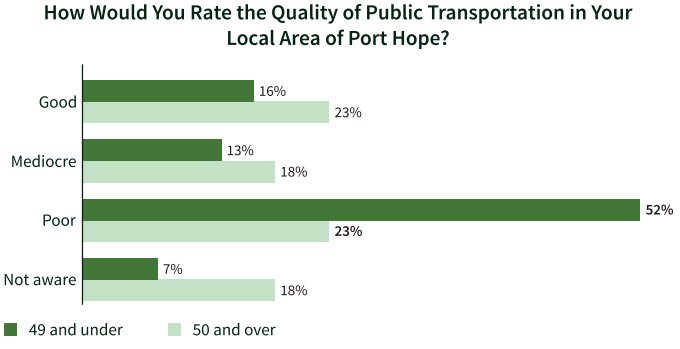


Figure 13. Distribution of survey participants' opinion on the performance of public transportation based on age. Source: Figure by authors.

3.5. Area of Residence

Climate change perception is also influenced by the environment people live in (Palm et al. 2017). The places we live, unusual weather conditions, or catastrophic events related to climate change, and the social memory that a combination of all these aspects has formed, have a significant impact on building climate change perception in communities. This phenomenon becomes more critical when investigating human behavior and how communities react to climate change. Research illustrates that communities that previously experienced catastrophic climate change events tend to act differently and have different perceptions (Bukvic and Harrald 2019). Similarly, Elrick-Barr et al. (2015) reported that the risk perception of climate change can still be differentiated and tends to be higher for equally vulnerable coastal communities if one has previously experienced climate hazards. The relationship between high climate change risk perception and being in close proximity to coastal areas or living in flood-prone areas has been identified as limited and relatively weak (Brody et al. 2008). In addition, unpredictable weather conditions such as hot summer days and warmer winter days or, oppositely, colder winter seasons make people more concerned about climate change (Hamilton and Keim 2009).

Even though it seems that all these aspects can be linked with social memories and previous experiences, there are studies showing that these memories can be manipulated and changed by many factors (Palm et al. 2017). Research shows that increased perception is temporary if the extreme weather events' duration is shorter

than two weeks, irrespective of their intensity, for instance, Snowmageddon and Superstorm Sandy (Deryugina 2013; Trenberth et al. 2015). Similarly, subsequent cold winter experiences can erase the memories of hot summer days. People generally lose their interest and see climate change problems as non-threatening and non-occurring events as they do not suffer the permanent consequences (Brody et al. 2008; Saad 2015).

Nonetheless, for rural communities, shared social memories of these kinds of events help improve climate change risk perception, cooperation, and adaptation (Bukvic and Harrald 2019). Although rural places are relatively less affected by climate change simply because of somewhat limited urbanization, they are still more vulnerable to deleterious effects caused by climate change due to their higher dependence on natural resources, limited economic diversification, older populations, and fewer institutional resources (Bukvic and Harrald 2019; Lal et al. 2011). Furthermore, rural areas can also be more fragile when it comes to flooding events, as they can have significant impacts on an economic, social, and cultural scale in these less-populated areas (Bukvic and Harrald 2019).

Overall, we observed only slight differences between the urban and rural respondents to this survey and that they generally agreed on most issues. The only remarkable difference was the lack of information about the quality of transit systems by the rural respondents (Figure 14). Almost 20% of respondents in both urban and rural areas stated that they were unaware of any action from the private and public sectors to address climate change. Similarly, 40% of survey respondents also stated that they did not know what the Municipality of Port Hope was carrying out to address climate change and its impact. These two findings are clear indicators that general knowledge about what the municipality is carrying out to address climate change is low. Given the general lack of knowledge and unwillingness to follow the climate change situation in social media, the reasons behind these issues should be further researched and discussed.

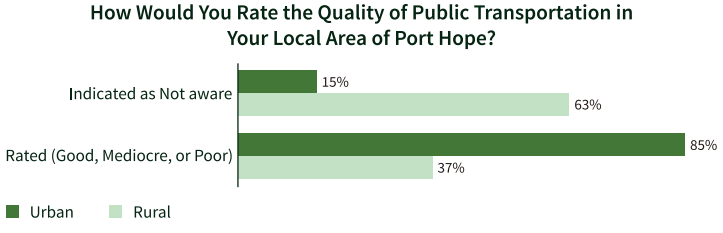


Figure 14. Distribution of survey participants' opinion on the performance of public transportation based on the area of living. Source: Figure by author.

3.6. Limitation of the Survey

This study summarizes a comparative analysis of local community survey findings as of May 2021. It does not reflect any changes to community activity, educational programs, policy, or perceptions after this date. Furthermore, while efforts were made to include multiple representations, some specific views may have been missed. In particular, the age demographic may not be representative of the community as the survey results did not include a comparable population of youth in Port Hope who may be undergoing an updated environmental and climate-related education curriculum. The discrepancy in the financial status representation could also impact identifying priorities for the local community.

4. Conclusions and Recommendations for Action

Based on our findings, a set of recommendations are articulated to serve as input to the planning and development of a climate plan by the Municipality of Port Hope for addressing both mitigation and adaptation strategies applicable to the region. These recommendations reflect core elements of global climate commitments. The community-driven strategies outlined here (including nature-based solutions, low-carbon mobility, and inclusive planning) mirror key pillars of the Paris Agreement and align with Sustainable Development Goals such as SDG 11 (Sustainable Cities), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). This underscores the value of municipal-scale planning as a mechanism to activate and localize global environmental objectives. Grounded in similar challenges globally, these recommendations can be directed at a wide range of decision makers and stakeholders, including local and regional authorities, businesses, grass-roots organizations, and civil societies. These are intended as adaptable planning priorities rather than fixed implementation models and should be interpreted according to each municipality's resources, political structure, and community context. In light of the outcomes of the 2021 United Nations Climate Change Conference (also known as COP26) and to accelerate action towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change, the first and most important action is to prioritize climate change as a lens for all future municipal planning.

The creation of a transport management association can help develop a low-carbon transportation plan for local businesses, schools/colleges, and municipality staff. If the majority of the community are known to be open to on-demand transportation services and cycling, incorporation and further innovation in these areas are viable additions to a climate change strategy. Investment in EV infrastructure should be assessed on a community need basis.

There should be a plan for awareness building around digital literacy as well as local climate change actions through online media, with plans to properly transition from traditional media forms. Core climate change knowledge should be embedded in public platforms and local news channels to gain public trust and understanding, followed by creating dedicated opportunities and spaces for climate engagement among youth and younger demographics. Community engagement programs should be instituted to raise awareness about municipal climate change action plans, if they exist. Adequate consideration must be given to the financial insecurities of low-income households around affordable housing, support for vulnerable populations, and limiting increases in taxes.

There is a growing interest in soft engineering solutions among the community. Collaboration opportunities should be explored with local organizations and academia to advance the implementation of such solutions further, which can attract and further engage the highly educated group and create trust and optimism. The creation and maintenance of a complete record of existing green space and setting a yearly target for new tree plantings in public and private spaces are among various methods of community engagement in increasing improving natural infrastructure. In rural areas and farmlands, investing in agroforestry, creating and maintaining tree planting incentives on and around agricultural land, and green energy incentives can help protect farmers and agricultural communities from the impacts of the changing climate.

The impacts on low-income households resulting from a carbon tax should be minimized by helping to finance a transition to clean energy production. Existing incentives for natural gas usage should be eliminated, since natural gas generates greenhouse gases; alternatives should be provided at an equally affordable rate. Furthermore, attention should be paid to increasing community awareness in Port Hope about the impacts of individual behaviors on climate change, specifically among those with university-level education. It can be beneficial to conduct workshops for this particular cohort and present scientific and evidence-based opportunities to encourage participation. Local businesses should be incentivized to pursue higher green standards despite the marginally higher costs for local consumers.

Studies state that the complexity and subjectivity of climate change perception is highly dependent on both demographic and anthropogenic factors. In this study, we focused on Port Hope, located in a developed country with a history of flooding incidents. Like many other Canadian municipalities, Port Hope faces a number of ongoing severe environmental challenges execrated by climate change, such as aging

infrastructure or demands for more affordable, adaptable housing (FCM 2016). The community-focused approach to inform municipal climate action planning not only improves the social outcomes of the plans but also reduces the implementation risks for the local governments.

Overall, the community represented in this study is well informed about the nature and implications of climate change in the region and has definitive expectations for the municipality for mitigation and adaptation via a climate change action plan. The overarching outcome of the study can address the importance of integrating community in the early stages of planning, provided that a robust public relations strategy is devised for establishing diverse methods of inclusion and outreach.

Integrating community engagement into climate action planning presents a unique opportunity to increase the sense of ownership and acceptance within all levels of society while delivering important co-benefits that will support communities, the environment, and contribute to greenhouse gas reductions. By designing the process with community integration in mind, planners and decision-makers can access tailored solutions for locally emerging issues that reflect a broad spectrum of interests and secure broad community, stakeholder, and council support.

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Towards 2030: The Effective Employment of ICTs in Influencing Climate Action Among Rural Communities

Sharon Tshipa and Olekae T. Thakadu

1. Introduction

Burning fossil fuels, among other human activities, contributes to the increase in the concentration of greenhouse gases in the atmosphere; CO_2 concentration has exceeded 400 parts per million (ppm) (Mikhaylov et al. 2020). As a result, the globe is on track to reach 2 °C by 2050, particularly given that current mitigation pledges for 2030 are estimated to deliver only one- to two-thirds of the emissions reductions necessary to limit warming to safer levels (Black et al. 2021). In 2015, climate science suggested that global warming had reached 1 °C above the preindustrial period. This came at a time when prominent climate impacts under a warming of 1 °C included floods, limited rainfall, recurring drought, heatwaves, coral bleaching, and cyclones; at 2 °C, the impacts are expected to worsen, triggering multiple tipping points (e.g., see Akinyemi and Abiodun 2019; Post et al. 2019).

The present and looming threats to human rights to life, health, adequate food, housing, and culture have since compelled development stakeholders to come up with strategic and innovative methods to communicate practical adaptation and mitigation measures to the masses (Galeon et al. 2019; Ghosal and Kumar 2020; Wakili et al. 2020; Yohannis et al. 2019). Although 'adapting to climate change taking place on timescales of decades is far more challenging than adapting to changes that take place over thousands of years' (Dutton Institute 2024), inclusive climate action was viewed as imperative.

The Role of ICT in Climate Action

In motivating climate action, governments, civil society organisations, and scientists in partnership with journalists have taken advantage of ICTs. These include television, radio, newspapers, the internet, and cell phones that have since become accessible even to remote and poor individuals, as in the case of countries in Latin America, South and East Asia, the Pacific region, West and Sub-Saharan Africa (Devkota and Phuyal 2018; Dittoh et al. 2019; Galeon et al. 2019; Gangopadhyay et al.

2019; Hoang 2020; Lwoga and Sangeda 2019; Sousa et al. 2019; Tumbo et al. 2018; Yohannis et al. 2019).

Empirical research motivated by the adoption of ICTs in communicating climate change posits that ICT is a critical and essential tool for sustainable development as it has the potential to reduce poverty and improve livelihoods by empowering users with timely knowledge while providing appropriate skills for increasing productivity (Hoang 2020; Majeed 2018; Olojede et al. 2017). This is because, among a myriad of plausible uses, ICTs such as the radio, television, and mobile phones (often emerging as the top three prevalent ICTs in receiving climate change messages) have been employed to deliver knowledge about renewable energy, temperature, rainfall, drought, and crop and livestock management in the face of climate change (Devkota and Phuyal 2018; Titifanue et al. 2017; Tyagi 2021). This is among other measures supporting resilience.

Furthermore, systems were also developed to provide weather information through voice prompts in local languages, and educational videos (video and Bluetooth technology) on mobile phones have been used as an effective way to promote sustainable practices by facilitating innovation uptake (Dittoh et al. 2019; Sousa et al. 2019). This success did not come without question. Some scholars (e.g., Coroamă et al. 2020; Moletsane 2019; Shehzad et al. 2020) raised concerns about the materiality of ICTs as environmentally hazardous machines whose current share of global greenhouse gas (GHG) emissions (an estimate of 1.8–2.8%) is underestimated by possibly 25% (Freitag et al. 2021). Hence, there is a need for green ICTs (N'dri et al. 2021).

Given the registered global wins in inspiring climate action, the current study investigated effective pathways of employing ICTs in influencing climate action among residents of the Okavango Delta community of Shakawe. The specific objectives were to (i) assess climate change awareness among local communities in Shakawe; (ii) explore climate change activities among Shakawe residents; (iii) examine sources and channels of climate change messages among the residents; and (iv) examine factors influencing the uptake of mitigation and adaptation strategies among the residents of Shakawe.

Activities considered by this study are inclusive of recycling, discriminate dumping of waste, cycling, climate-friendly diets, growing drought-tolerant crops, the continuous feeding of cattle, and the use of solar energy and biodegradable shopping bags, among other practical efforts that can be undertaken by individuals.

The current study was also motivated by the fact that previous worldwide studies on ICT have been limited to energy, fisheries, disaster risk reduction, waste

management, loss of biodiversity, and mostly agriculture, as the latter is considered to be highly sensitive to climate change (Amin and Rahman 2019; Bastida et al. 2019; Galeon et al. 2019; Gangopadhyay et al. 2019; Kassem et al. 2019; Lawo et al. 2020). Other studies have assessed the role of ICT in climate change adaptation and mitigation, especially in terms of educating and the delivery of climate change messages (Alant and Bakare 2021; Arogyaswamy 2021).

Research conducted in Botswana has mostly focused on the environment in general; hence, this study investigated effective pathways of employing ICTs in influencing climate action by exploring climate change-conscious activities being undertaken among Okavango Delta dependent communities. If humanity is to successfully achieve global decarbonisation, this study argues that greater emphasis must be placed on showcasing activities that contribute to environmental preservation, as these can serve as catalysts for sustained and expanded climate action. This is especially true because ICT for development (ICT4D) and ICT for sustainable development (ICT4SD) frameworks have the capacity to make the attainment of the SDGs possible (Kostoska and Kocarev 2019; Rothe et al. 2022). The frameworks do not only offer scalable solutions for advancing climate-smart agriculture, disaster preparedness, and early warning systems in climate-vulnerable regions (Bashiru et al. 2024; Wanyama et al. 2024); for a while now, ICTs have also enhanced participatory governance in sustainable development by enabling interactive feedback loops between communities and policymakers through mobile apps and open data portals (Vito 2018). Thus, this innovative role largely influenced the current study's focus on understanding localised ICT use in fostering climate-responsive behaviours among remote communities.

2. Materials and Methods

2.1. Theoretical Framework

The conceptualisation and development of this study were guided by the Normative Integrated Structural and Participatory Model for Climate Change Communication (SPCCC). This framework model was formulated upon the realisation of the need for an integrated structural approach, as it was deemed that no single paradigm can lead to effective communication, and no one explanation or methodology can be applied considering the complexity of the world today (Evans et al. 2018). The current study adopted this framework on the basis of the current proliferation of ICTs (Evans et al. 2018).

The framework presents the media as central to the communication process, with the media acting as the marketplace for ideas and providing a platform for engagement and debate (Evans et al. 2018). This theoretical perspective takes into consideration all forms of media, not just in reference to media practitioners such as journalists but also in reference to media as printed, electronic, or web-based channels of communication: traditional and modern forms of ICT (Freeman 2018; Singh and Pandey 2017). In this way, journalists, as avid users of ICT (see Obayi et al. 2018; Williams et al. 2021), are a common repository of content that is eventually delivered to the publics. Though the media, in all forms, remains central to the communication process, in an ideal context, Evans et al. (2018) suggest that participants in the discourse, including policymakers, ordinary citizens, experts/scientists, civil society, and the media themselves, should engage equally and in a dialogic manner, based on the principles of reciprocity. Ideas from the experts/scientists, policymakers, civil society, and ordinary people, the writers further posit, should enter the media for discussion with an equal opportunity for engagement and debate, as opposed to privileging one group at the expense of the other.

This hybrid climate change framework was opted for because it acknowledges that no one single model of communication can best be utilised for development and social change (Evans et al. 2018). It pools the strengths of theories such as the risk communication, development journalism, advocacy journalism, environmental journalism, and communication for development and social change theories and perspectives, building on the advantages of both bottom-up and top-down processes (Evans et al. 2018).

This integrated framework acknowledges development journalism by borrowing the view that climate change communication should engage and empower people in the process of climate change policy formulation, mitigation action, and adaptation solutions (Evans et al. 2018). Inspired by development journalism theorists, the SPCCC is designed to empower grassroots communities, where the localisation of the Sustainable Development Goals (SDGs) and meaningful social change must occur. This approach recognises that limited climate action at the grassroots level is often linked to the exclusion of these communities from critical discourses and decision-making processes in which they should actively participate (Evans et al. 2018). This view guided the development of this research's objective to explore climate change-conscious activities carried out by the Okavango Delta community of Shakawe in an effort to fight climate change after being informed and encouraged by messages from diverse climate change sources, delivered through varied ICT channels.

2.2. Study Area

This study was conducted in Shakawe, a large fishing village located in Ngamiland district in the Northwestern part of Botswana (Figure 1). The Ngamiland District is popular for being the home to the Okavango Delta, a World Heritage and Ramsar site of major importance. The Okavango Delta is described as an inland wetland that is of international, regional, and national importance because of its diverse biodiversity, ecosystem services, and its significant contribution to human livelihoods (Rutina et al. 2016). The delta is both a permanent and seasonal home to a wide variety of wildlife, fish, bird, and plant species (Quammen 2017; Rutina et al. 2016; Wolski et al. 2006). Local communities are dependent on the delta for their livelihoods. Other than Shakawe, others include settlements like Shorobe, Boro, Xubu, Tubu, Mohembo, Gumare, Sepupa, and Seronga, among others, all of which are on the fringes of the Okavango Delta (Thakadu et al. 2015).

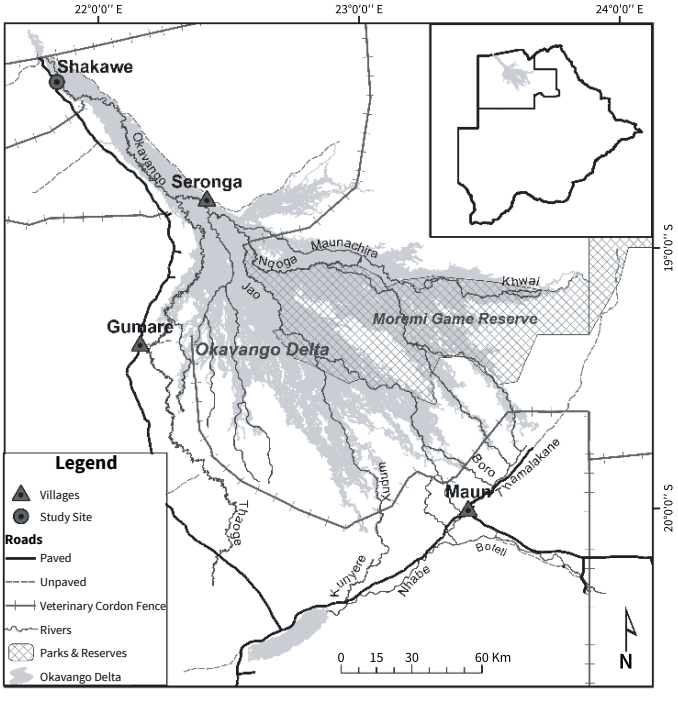


Figure 1. Map of the study area. Source: Authors' compilation based on data from ORI GIS Laboratory.

Despite their "access" to water, a scarce resource in the country, these communities are also experiencing the effects of climate change, such as rising temperatures, limited rainfall, floods, and heatwaves (Moses and Hambira 2018; Motsholapheko and Ngwenya 2021; SAREP 2014). These effects tamper with the livelihoods of the residents as most depend on the natural resources they find along and within the delta (Tshipa 2023). The economic activities being affected by climate change in these communities are tourism, fishing, and agriculture-related activities, such as dry land farming, *Molapo* farming, and livestock rearing. Subsistence agriculture is the major source of livelihoods among Delta communities (Tshipa 2023).

Shakawe hosts the second largest human population of 10,589 residents (a rise from 6693 in the 2015 national census) in the Okavango sub-district, following Gumare, which hosts 11,572 people, a rise from 8970 (Statistics Botswana 2022). Given the fact that its population is largely battling multidimensional poverty, when equated to that of Gumare, this study posits that the residents of Shakawe have pressing reasons to adapt and mitigate and more motivation to undertake climate change-conscious actions like conservation, as promoted by ICT-delivered measures. The village also stood out because its proximity to the delta is much more significant in contrast to that of Gumare.

Regarding ICT, it is important to note that Shakawe enjoys the presence of three of Botswana's mobile networks—Botswana Telecommunications Corporation (BTC), Mascom, and Orange—though the fibre network largely runs along major highways on the western side of Botswana (Kereteletswe 2015; Mpoeleng 2016). The presence of Mascom brought with it Kitsong Centres in an effort to transform the village into a knowledge economy while empowering the youth and supporting the Vision 2036 pillar 'Sustainable Economic Development' by enabling digital literacy.

2.3. Study Design

This study was cross-sectional in its approach, meaning that data were collected from the respondents at one single point (Creswell 2014). A mixed-methods design was employed where both qualitative and quantitative data were collected to facilitate a better, broader, and more comprehensive understanding of the research phenomenon (Alexander et al. 2015; McKim 2015). The mixed-methods design was used because it facilitates triangulation, complementarity, and expansion, which cannot be attained while using one approach, i.e., either quantitative or qualitative approaches (Ary et al. 2014). Specifically, a convergent parallel mixed-methods design was used where both qualitative and quantitative data were collected,

data analysis was conducted separately, the results were compared and contrasted accordingly, and interpretations were made (Creswell 2014). The design is accredited for enhancing validity and corroboration through triangulation (Ary et al. 2014; Demir and Pismek 2018), thereby ensuring rigor.

2.4. Sampling

2.4.1. Key Informants

Key informants were sampled using a purposive sampling technique. Key informants were drawn from professionals in the environmental sector (expert sources of information) and traditional leaders in Shakawe (as their formal role exposes them to the information being sought by the researcher) (Palinkas et al. 2015). Twenty-one (21) key informants were interviewed. These participants represented the media, government, civil society organisations, DiKgosi (traditional authorities), embassies, and intergovernmental organisations.

2.4.2. Household Respondents

Households were sampled using a random sampling method from a population of 1487 households compiled by the Okavango Research Institute (ORI) in 2018. The household listing was updated to cater for new households. Households were numbered consecutively, and a random sample of 316 households were selected using the Star Trek Random Number Generator application. The sample size was determined using Yamane's formula (Yamane 1967), employing a confidence level of 95% and p = 0.05.

$$n = \frac{N}{1 + n\,(e)^2}$$

where n = sample size; N = population size, and e = level of precision from each sampled household; any willing representative found in the household over the age of 18 years participated in the interview. While the 18 years of age threshold ensured youth participation and perspective, it was chosen as it is the legal adulthood age in Botswana where an individual can consent and make informed decisions.

2.5. Data Collection Methods

Primary data were collected using directly administered semi-structured questionnaires for the household survey. For key informants, qualitative data were gathered using an open-ended interview guide. Participant observation

(direct observation) was used, and it allowed for noting the subtle responses of the respondents during interviews.

A list of 13 open-ended questions on the various domains of climate change communication, such as 'What informs/influences your ICT preferences in reaching out to the masses, if at all?', 'Would you say recipients/end-users of your climate change messages trust the ICT channels you use?', and 'Are you satisfied with your target recipients' climate change awareness?', guided the conversation with key informants. For the household survey, the questions used were adapted from existing studies (see Agha et al. 2018; Bojovic and Dooel 2014; Davis 2014; Duan 2018; Fanoberova and Kuczkowska 2016; Gutierrez 2016; Israel and Wilson 2006; Marzetta 2016; Palinkas et al. 2015; Wilkins et al. 2018). These measured the respondents' knowledge, level of climate change awareness, satisfaction, attitudes, and source trustworthiness. Wilkins et al. (2018) posited that trust in sources helps to determine how likely it is that someone will accept the information being presented, and it can also affect the likelihood of behavioural change based on the information. The trust question was crucial in this current study as it sought to find out if respondents were adapting and mitigating, given the information channelled (through modern and traditional ICTs owned such as television, radio, cell phone, social media, online news publications, and newspapers) to them that influences climate change-conscious activities. The household survey was captured digitally using the Kobo Toolbox accessed through tablets and Android cell phones.

Prior to this study, the questionnaire was pre-tested in Matlapaneng village. This village stood out because of its access to traditional and modern forms of ICT and its dependency on the Okavango Delta as a source of livelihoods such as basket weaving, fishing, tourism, Molapo farming, and arable and livestock farming, which are now being threatened by climate change, increasing the vulnerability of the poor to livelihood insecurity (Kgathi and Motsholapheko 2011; Cassidy et al. 2011), making this village similar, in terms of key characteristics, to the target study site. A total of 30 household respondents from 3 wards in this village were interviewed. This pilot study was undertaken to assess the study's feasibility, and the adequacy of survey instrument developed, as well as serving as training for the researchers (In 2017; Van Teijlingen and Hundley 2002). The questionnaire was adapted based on the outcome of the pilot study.

2.6. Data Analysis

Qualitative data from interviews were analysed using Atlas.ti 8 (a qualitative data analysis and research software) and coded through a qualitative content analysis

approach. This entailed the reduction and organisation of the data, synthetisation, searching for significant patterns (e.g., types of ICT channels used to receive climate change messages and the frequency at which messages were received), and the discovery of what is important. The stages of qualitative data analysis were adopted from Wolcott (1994).

Quantitative data were managed and analysed using the Statistical Package for Social Sciences (SPSS) version 26. Data were analysed using both descriptive (e.g., mean, proportions, frequencies) statistics to summarise and describe sample characteristics and inferential statistics (chi square and logistic regression) to explore associations and assess differences between groups. Assumptions underlying the respective statistics were tested and found to be tenable.

3. Results and Discussion

3.1. Socioeconomic and Demographic Characteristics

The purpose of this study was to investigate effective pathways of employing ICTs in influencing climate action among the residents of the Okavango Delta community of Shakawe. A total of 303 respondents from 11 wards in Shakawe village were interviewed. The age of the Shakawe respondents ranged between 18 and 94, with a mean of 41.36 (SD = 16.42, n = 303) years. The majority of the respondents were female (69.6%, n = 211) (Table 1).

Table 1. Summary of socioeconomic and demographic characteristics of quantitative respondents (N = 303).

Age Group (Years)	*N*	Percent (%)
18–30	5	1.7
31–40	87	28.7
41–50	78	25.7
51–60	60	19.8
60+	73	24.1
Gender	***N***	**Percent (%)**
Male	92	30.4
Female	211	69.6

Table 1. *Cont.*

Education Level	*N*	Percent (%)
Primary	57	18.8
Junior secondary	95	31.4
Secondary	70	23.1
Tertiary	28	9.2
None-formal	12	4.0
Never went to school	41	13.5
Source of Livelihood	***N***	**Percent (%)**
Government employee	17	5.6
Private business employee	24	8.0
Agriculture/crop	16	5.3
Agriculture/livestock	5	1.7
Tourism	3	1.0
Artifacts creation	4	1.3
Other	134	55.4
None	65	21.7
Monthly Earnings (BWP)	***N***	**Percent (%)**
0	127	41.9
51–800	85	28.1
801–1500	38	12.5
1501–3000	26	8.6
3001–4500	14	4.6
4501–6500	6	2.0
6500+	7	2.3

Source: Table by authors.

Though the poverty gap between males and females is largely not significant in Botswana, these proportions can be attributed to the fact that a good number of women, compared to men, are unemployed (especially in villages), meaning that they are often at home during working hours, as most interviews were carried out during working days and hours (Statistics Botswana 2021). A crosstabulation of the 'gender' by 'source of livelihood' indicated that at least 40.3% of the female respondents had no source of livelihood, compared to 34% of the men. These results were not

surprising as previous research by Statistics Botswana indicated that in the year 2011, 1267 men in Shakawe village were employed compared to 823 women (Statistics Botswana 2015). Though a high proportion of females in the sample are unemployed, some of them indicated that they were involved in other informal entrepreneurial activities such as catering, running a tuckshop, domestic work, plaiting hair, and street vending, while others are dependent on relatives and government safety nets for survival, among other livelihood alternatives.

Since poverty rates decline as education increases, literacy rates in the study area are not entirely disconcerting as the findings depict that a high number of respondents have received some form of education—registering an education level mean value of 2.89—indicating that the majority went above the primary school educational level, i.e., seven years of basic education (Table 1) (Statistics Botswana 2021). This is not astonishing as the literacy rate in Ngamiland, though the lowest in the country, is over 70% (Statistics Botswana 2018). Nevertheless, 13.5% (n = 41) of the respondents had never been to school, a target audience that climate change communication should take into consideration.

3.2. Leveraging ICT in Climate Change Action Among Rural Communities

3.2.1. Climate Change Awareness

Overall, the work of promoting climate change awareness by transmitting information on several pressing topics such as drought, fires, heatwaves, overgrazing, water, and conservation, by sources of climate change information, has yielded some positive results that can promote the localisation and advancement of the SDGs. This is suggested by the fact that many of the respondents strongly agreed or agreed that limited rains, floods, droughts, season shifts, heatwaves, cyclones, and extreme or high-intensity rainfall were caused by climate change. A large number agreed that heatwaves (41.9%, n = 127), limited rains (42.9%, n = 130), droughts (42.9%, n = 130), floods (39.6%, n = 120), seasons shift (49.2%, n = 149), cyclones (36.3%, n = 110), and extreme or high-intensity rainfall (44.9%, n = 136) were caused by climate change.

Nevertheless, 25.7% (n = 78) were neutral about floods, 23.4% (n = 71) were neutral about extreme or high-intensity rainfall, while 28.7% (n = 87) were also neutral about cyclones, as they were uncertain about climate change being the cause. Regardless, all factors have high mean values ranging between 3.74 and 4.18, indicating a high level of climate change awareness in this regard. In their study, Bojovic and Dooel (2014) also found that most participants follow climate change-related activities and policy in their country (84%); hence, a high number

reported that they were well informed about different issues related to climate change such as causes, consequences, ways to fight, and ways to adapt. The majority reported that they were well informed to some extend (Bojovic and Dooel 2014).

Regarding all the effects listed above, the majority of the respondents of the current study ranked the shift of seasons (85.5%, n = 259), drought (79.9%, n = 242), and heatwaves (58.8%, n = 178) as the most important climate change threats to their community, while cyclones (79.2%, n = 240) and floods (59.7%, n = 181) were ranked as the least possible threats, as emphasised by the climate change messages they receive through ICTs they have access to, such as TVs, as employed by DS1:

> On TV we have a programme that airs every Sunday and Monday where topics on drought and climate change are also discussed (DS1).

On the other hand, the participants of a study by Bojovic and Dooel (2014) ranked shifting seasons (76%) and temperature (72%) as some of the major changes they had noticed in the environment or climate over the past 10 years. Droughts ranked fifth at 36% after rain (66%) and floods (54%) in their study but ranked second in the Botswana context. This is not surprising as climate change-induced droughts have since become the greatest hazards to Botswana's poverty eradication and development efforts. For example, between 2010 and 2020 alone, Botswana only had one partial drought year, which was the 2016–2017 period, and two non-drought years, in the 2013–2014 and 2019–2020 periods (BOPA 2019, 2020; Statistics Botswana 2020). Despite these seasons being declared non-drought, some parts of the country that did not receive adequate rainfall during these times were declared drought-stricken (BOPA 2019, 2020). All in all, these findings suggest that ICT4SD has enhanced climate change awareness among Shakawe residents by facilitating access to environmental information and supporting inclusive education. With further widespread use, the results suggest that ICTs will significantly bridge knowledge gaps and further empower communities to share indigenous knowledge and the local experiences of climate variability, thus fostering a deeper understanding of climate risks and appropriate responses. These possibilities underscore ICT4SD's transformative role in not only raising awareness but also inspiring behavioural change and collective climate action (Balogun et al. 2020).

3.2.2. Implementing Climate Change Activities

In using radio and television to deliver climate change messages, DS1 advises "farmers in ways that allows them to manage their grass, so that during winter times they can still have something to feed their animals". For this development stakeholder, the effects of drought on cattle production are of major concern because

Botswana's incessant droughts, as exacerbated by climate change, threaten the country's economy, traditions, and culture (Statistics Botswana 2020; Tshipa 2019). The country's estimated traditional sector cattle population has since dropped from 2635 million in 2010 to 935,000 in 2019 due to high mortality rates mostly attributed to droughts (Statistics Botswana 2020). The number of households rearing cattle has also plunged, from about 75,500 in 2004 to 39,000 in 2015, a more than 45 percent decline (Statistics Botswana 2020; Tshipa 2019). Between 2017 and 2019 agricultural seasons, a further decline was witnessed from 33,819 households to 29,355 (Statistics Botswana 2020).

While the population of cattle is dropping, that of browsers like goats, which cope better with droughts, is on the increase, though the number of holders (for both goats and sheep) is declining. Some traditional farmers have quit the sector and resorted to government safety nets in order to survive. To ensure that cattle production continues to significantly contribute to Botswana's socioeconomic development, DS1, through radio and TV, tells "farmers to supplement, to grow Lucerne, Lablab or Rhodes grass for animals". Some farmers in the region who received the adaptation messages delivered by DS1 have since taken to the production of these grasses, yet none of the Shakawe household respondents are growing feeds for livestock. However, some admitted to the culture of allowing their cattle to graze the remains of what they would have managed to harvest that ploughing season.

> A farmer here in Ngamiland is growing Brazilian grass, it is very resistant of climate change, and has great forage value. Other farmers in Maun, Kuke and Chanoga are growing lablab, and Lucerne, and Buffalo grass (DS1).

Supplementary feeding (37.7%) as an adaptation strategy was also found among households in the Bobirwa sub-district of Botswana, including destocking (41.3%) and the temporary migration of livestock in search of better pastures and water (36.5%), to cite a few solutions (Mugari et al. 2020).

Climate change-conscious actions like these, as acknowledged by DS1 in the current study, were not the only ones listed. DS7 disclosed that some recipients of climate change messages protected their sorghum and millet (which are drought-resilient) from being consumed by birds, as opposed to growing maize which requires ample water to grow. Nevertheless, almost one-third of the respondents in Shakawe village, 32.7% (n = 99), are adopting drought-resilient crops. Contrary to these results, Mugari et al. (2020) found that the majority of households in the Bobirwa sub-district adopted drought-tolerant crop varieties (72.6%), followed by early-maturing crops (70.6%).

The fact that most climate change messages—especially by government departments—target farmers, however, does not cloud other efforts such as citizens' attempts to preserve forests by only collecting dry and stipulated types of wood, the conservation of water and electricity in the home, as witnessed by DS15, craft weaving using recycled materials, as mentioned by DS20, tree planting in the home, as noted by DS2, and the use of solar energy, as inspired by DS18, among other activities, inclusive of the growing interest in bio-gas production.

Though the government retreated from its plastic shopping bag ban, which was supposed to come into operation on 1 November 2018, the survey results reveal that in an effort to reduce plastic usage, a small number of residents have stopped using plastic bags (5.6%, n = 17) in favour of environmentally friendly packaging alternatives. Recycling campaigns in general have been favoured by a high number of people, as 43.6% (n = 132) of the respondents indicated that they are involved in some form of recycling. The most common items that are recycled include cans, bottles, and plastics; these are mostly reused by women to create crafts and other souvenirs sold to tourists. Waste recycling was also found to be prevalent (56%) in a study by Bojovic and Dooel (2014) who asked participants if they consider the environment and in particular climate change through using alternative transport modes (64%), such as cycling, walking, or public transport; reducing water (60%) and energy consumption (57%), and recycling. Other activities that have paid off in the current study are conservation messages often delivered through SMS by the Botswana Power Corporation (BPC) and tree planting initiatives by the Department of Forestry and Range Resources. This is because the majority of the participants are planting trees (55.8%, n = 169), though they are not satisfactorily knowledgeable on the role of trees in fighting climate change, and those with electricity in the home tend to unplug devices when not in use (50.2%, n = 152), while 45.5% (n = 138) of the participants continue to use energy-efficient light bulbs.

The plausible use of energy-efficient appliances by the respondents was also highlighted by Musova et al. (2021). A review by Bastida et al. (2019), on the other hand, found that ICT-based effects on consumer behaviour can reduce household final electricity consumption by 0–5%. Their findings further suggested that ICT-based interventions in household energy use could contribute between 0.23% and 3.3% of the EU CO_2 reduction target from the energy sector that would keep warming under 1.5 °C. In the current study, however, most respondents admitted that they conserve electricity because the practice saves them money. This is largely because they are unaware of the role of fossil fuels in global warming. Lower

electricity bills are a mitigation benefit of energy saving, as also alluded to by Kondo et al. (2021).

Efforts to adapt and mitigate by Shakawe village respondents are commendable but far from adequate. This was also acknowledged by the participants themselves, as slightly over two-thirds indicated that they were not at all satisfied with what citizens in their community are doing in order to mitigate and adapt, given all the messages on climate change they receive through ICTs (34.7%, n = 103). Though inadequate, the implementation of climate change activities by Shakawe residents demonstrates how global sustainability targets can be interpreted and operationalised at the community level. These local responses directly contribute to SDG 13 (Climate Action), while also supporting SDG 2 (Zero Hunger) through climate-resilient agriculture and SDG 12 (Responsible Consumption and Production) through recycling and reduced resource use. Altogether, these findings affirm that community-based responses, driven by accessible technologies and informed by local realities, are essential for making the SDGs actionable and meaningful in vulnerable, climate-affected regions.

3.2.3. Sources and Channels of Climate Change Information

Key informants revealed that the Botswana government has been playing a leading role in raising climate change awareness and promoting climate change-conscious developments in the country using ICTs. The household survey results, however, revealed that the local media is a leading known source of climate change messages by respondents (41.9%, n = 127), followed by the government at 33.3% (n = 101) (Figure 2).

The government as the second source somehow correlates with the findings of Thakadu and Tau (2012), who noted that government departments ranked the highest in disseminating environmental conservation messages of water, wildlife, fish, environmental health, and forest and veldt products' conservation to the public. The media's lead, however, is not surprising as the government often works closely with journalists to channel messages to specific audiences. Nevertheless, the findings further suggest that the government's leading role in disseminating information is due to the financial problems that some local NGOs and private entities find themselves battling. With a sufficient communication budget, some of the development stakeholders interviewed believe they can attain better climate change communication results:

> DS20: If wishes were horses, more could be achieved, funding is the limiting factor. We so wish the government, stakeholders, donors and sponsors can assist us in spreading conservation and climate change

messages as we deal with the most difficult community which is 60% semi-literate.

DS17: We have not yet been able to reach out as planned due to the limited financial resources, we believe that with a little funding our work has great potential to change attitudes and foster quick changes in individual transport choices to adopt cycling as a green transport.

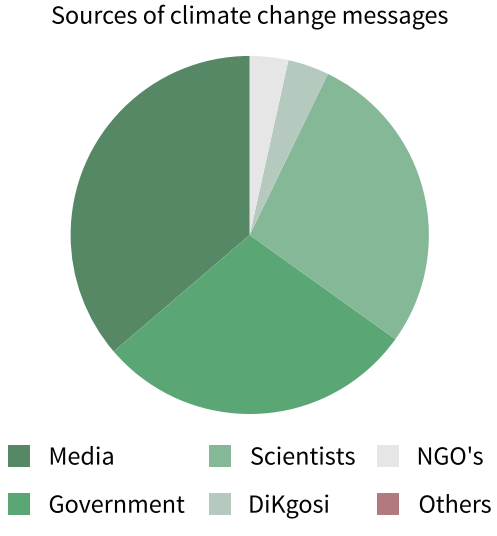


Figure 2. Leading sources of climate change news. Source: Figure by authors.

In the study by Thakadu and Tau (2012), only two NGOs were identified as sources by 2.5% of their respondents, yet still in the current study, NGOs also seem to be lagging behind in disseminating information as only a few respondents (4.0%, n = 12) indicated them as sources, a proportion which almost tied with traditional leaders—DiKgosi—at 4.3% (n = 13) (Figure 2). After the media and the government, scientists ranked third as a source at 32.0% (n = 97) (Figure 2). Politicians, international media, scholars, and intergovernmental organisations, all of which were excluded in Figure 2, sorely designed to depict leading players, ranked among the least. From the key informants' perspective, however, the latter seemed to be playing a significant role.

Respondents were further asked to rate their level of trust towards different sources of climate change information, as end-users and information-seekers consider source trustworthiness before accepting or rejecting the information, a finding reiterated by Fanoberova and Kuczkowska (2016) and Wilkins et al. (2018). The

government as a source was rated highest with a mean value of 4.08, while politicians, on the lower end, scored an average of 3.04, albeit still high. The majority of the respondents did not fully trust their sources of climate change messages, which is unfortunate as Fanoberova and Kuczkowska (2016) found source trustworthiness, among other variables such as source expertise and source attractiveness, to have a strong influence on attitude towards using information source. What this points to is perhaps that trust in human sources and institutions has been on the decline for decades, as revealed by Wilkins et al. (2018), who noted a decline in the U.S. from 1972 to 2012.

Asked whom they trust completely among their identified sources, the government had the highest number of respondents (15.8%, n = 48), indicating that they trusted the Botswana government in this study, followed by local journalists (15.2%, n = 46) and scientists (11.9%, n = 36). Contrary to these findings, Wilkins et al. (2018) found that the majority of people (64%) trusted scientific organisations either a lot or completely, followed closely by universities/educational organisations, while the lowest trust level was in the media. In the current study, politicians and international journalists (as opposed to local media) were indicated by an equal proportion (very few) of respondents (1.98%, n = 6), indicating that they were least trusted. The high trust levels in the government (who were found to mostly use radio, television, and newspapers to deliver climate change messages as they easily attract media coverage) and the media in this study may be because a high number of the respondents had junior and senior secondary school educational levels. This supposition is hinged on the findings that that those with more education are more likely to trust scientists/universities/conservation organisations (Wilkins et al. 2018).

As time goes by, development stakeholders fear that end-user trust may be lessened by fake news and/or infodemics. This is an undesirable aspect that DS16 is already grappling with:

> Radio communication is highly credible, as such end-users are comfortable with getting information via radio stations as opposed to social networking apps. Fake pages have been setup in our name before, confusing people, so now we are holding back on delivering climate change messages using social media. We are only using Radio and TV etc.

Considering this, the current study calls for the implementation of precautionary measures as the trustworthiness of ICT message sources is critical in the localisation of the SDGs because credible and reliable information fosters community buy-in, encourages behavioural change, and ensures sustained engagement with development initiatives. Conversely, the spread of misinformation or

infodemics—especially through social media—can undermine public confidence, distort scientific understanding, and lead to resistance or apathy (Islam et al. 2020) towards climate actions and other SDG-related efforts. This erosion of trust compromises informed decision-making and can derail progress towards achieving the SDGs, particularly among vulnerable communities of Shakawe where digital literacy is limited.

3.2.4. Factors Influencing the Uptake of Mitigation and Adaptation Strategies

Factors Influencing the Uptake of Mitigation

Logistic regression was performed to assess the influence of socioeconomic demographics on different mitigation activities (Table 2). Overall, the results showed (i) educational level and monthly earnings to be the only significant predictor of planting trees, (ii) gender to be the only significant predictor of stopping using plastic bags, (iii) monthly earnings and age to be the only significant predictors of the use of energy-efficient light bulbs, (iv) monthly earnings and age to be the only significant predictors of turning off lights when not in use, and (v) educational level to be the only significant predictor of recycling (Table 2).

Since most ICTs in Shakawe village are owned by men, and while most of the respondents are female, it is not surprising that men are six times more likely to stop using plastic bags than women. This is because men were observed to carry satchels and/or drive, while women seemed to think that there were no plastic bag alternatives. This result is in line with what Muriithi et al. (2021) highlighted about women's limited access to climate information, as the content channelled by development stakeholders does not adequately emphasise plastic bag alternatives.

Regarding the use of energy-efficient light bulbs, the odds ratio of 5.93 suggested that respondents who earn between BWP 1501 and 3000 are likely to confirm the use of energy-efficient light bulbs compared to those who do not earn a living. This finding corroborates the results by Zou and Mishra (2020), whose study revealed that rural households with higher per capita incomes and with a large household size and dwelling areas are more likely to purchase energy-efficient-labelled appliances than families with lower incomes and with a small household size and dwelling areas. Rural households with a higher level of education but relatively low incomes are less likely to purchase energy-efficient appliances (Zou and Mishra 2020). In their study, Ali et al. (2021) called for structured policy incentives (including flexible and lucrative schemes for consumers and manufacturers) and campaigns that highlight the financial benefits associated with energy-efficient appliances. They also touched

on the need for reasonable price and fiscal incentives to attract consumers towards energy-efficient appliances.

Table 2. Factors influencing decisions to accept ICT-delivered climate change mitigation measures.

Dependent Variable	Predictor Variable	B	S.E.	Wald	df	Sig.	Exp. (B)	95% CI for EXP(B)	
								Lower	Upper
I plant trees	Educational level	−1.66	0.49	11.55	1	0.00	0.19	0.07	0.50
I plant trees	Monthly earnings	−1.06	0.52	4.10	1	0.04	0.35	0.12	0.97
I stopped using plastic bags	Gender	1.89	0.65	8.60	1	0.00	6.63	1.87	23.49
I use energy-efficient light bulbs	Monthly earnings	1.78	0.68	6.91	1	0.01	5.93	1.57	22.37
I use energy-efficient light bulbs	Age	−0.71	0.35	4.06	1	0.04	0.49	0.24	0.98
I turn off lights when not in use	Monthly earnings	1.32	0.62	4.49	1	0.03	3.73	1.10	12.59
I turn off lights when not in use	Age	−0.88	0.37	5.57	1	0.02	0.42	0.20	0.86
I recycle	Monthly earnings	1.77	0.65	7.55	1	0.01	5.89	1.66	20.88

Source: Table by authors.

For those aged 40 and above, the odds ratio of 0.42 is less than 1, indicating that the youth (aged between 18 and 40) are less likely to report turning off lights when not in use. This finding is disconcerting as 'youth collective action has succeeded in: (i) problematising global climate inaction and inertia, (ii) framing climate change from a justice perspective' (Han and Ahn 2020), and (iii) winning climate litigation cases, while Shakawe youth remain highly inactive. In their study, Busch et al. (2019) found that 'students' grade level, and participation in clubs and a number of science classes primarily affected knowledge and social norms'. An implication of their study, that the current research agrees with, is that 'if action-taking is an intended outcome of climate change education efforts, then learning activities should address efficacy and social norms'. Without perceptions of environmental threat—often rendered by education—the youth are less likely to undertake climate-conscious activities, let alone participate in environmental protests (Haugestad et al. 2021).

When designing and packaging climate change messages targeting rural youth, it is therefore important for development stakeholders to bear this in mind.

In regard to recycling, results also showed educational level to be the only significant predictor of recycling (Table 2), indicating that respondents with a tertiary educational level are likely to recycle after receiving climate change messages through ICT compared to those with the primary educational level.

The strongest predictor of mitigation in this study is monthly income. Given that most of the respondents are self-employed, mitigation therefore becomes a challenge. Yet, if the respondents are fully made aware of the benefits of mitigation strategies such as conservation and recycling, among others, they can save their money and/or turn mitigation strategies into sources of livelihood. For Shakawe residents, recycling could easily become a stable source of income if Botswana had readily available buyers of waste. An observation made at the study site was of recycled bottles and cans piling up in homesteads, though they had collected them with the hope of selling, only to be disappointed by the fact that there are no buyers. If the Botswana government is going to continue telling people to recycle, it should ensure that there is a market and a recycling plant in the country.

Gender emerged as the second most significant predictor; development practitioners should therefore ensure gender equity in all they do, while bearing in mind that women have limited access to ICTs and climate information compared to men. This finding underscores the need for gender-sensitive approaches in localising the SDGs—particularly SDG 5 (Gender Equality) and SDG 13 (Climate Action)—by ensuring that women have equal access to ICTs and climate information to support informed participation in sustainability efforts (Jeevanasai et al. 2023). Persistent gender disparities in digital access and use—especially in rural and low-income communities—are marginalising women from decision-making processes and limiting their capacity to adopt climate-resilient practices, thereby threatening the inclusivity and effectiveness of SDG implementation (Jeevanasai et al. 2023).

Factors Influencing the Uptake of Adaptation Strategies

Logistic regression was performed to assess the influence of educational level, age, gender, and monthly earnings on adaptation activities employed by Shakawe respondents. Only two variables were significant predictors of climate change adaptation (Table 3). The first dealt with 'growing organic crops' as an adaptation activity carried out after receiving climate change messages through ICT; the full model containing all predictors was statistically significant, $\chi^2(13, N = 210) = 43.19$, $p < 0.00$. The explained variation in the model is 31.3% (Nagelkerke R^2); the model

as a whole correctly classified 85.2% of cases. The results showed gender and educational level as the only significant predictors of growing organic crops (Table 3). The positive coefficients were therefore an indicator that male respondents are 5.289 times more likely to grow organic crops after receiving climate change messages through ICT than women, while those with the junior secondary educational level are likely to do the same compared to those with primary school education. Education was also shown to enhance awareness of environmental and health benefits and facilitate access to agricultural knowledge and innovation (Sapbamrer and Thammachai 2021).

The findings have important implications for achieving the SDGs. Particularly SDG 5 (Gender Equality), SDG 4 (Quality Education), and SDG 12 (Responsible Consumption and Production), as they suggest that empowering women and investing in education can directly influence sustainable agricultural practices, which are key to food security and environmental resilience. Recent studies affirm this by showing that women often face structural barriers but are increasingly adopting sustainable practices when given equal access to training and resources (Areri et al. 2022; Tikon et al. 2023).

Contrary to the results by the current study, when Mittal and Mehar (2016) considered simultaneous decisions regarding coping strategies, they found that there is no significant difference between the male and female decision-makers when compared with the base category of a collective decision by all family members. For gender, their study also found no significant association with coping strategies (Mittal and Mehar 2016). Muriithi et al. (2021), on the other hand, suggested that male-headed households have a better opportunity to practice adaptation and access climate information, among others, more easily than female-headed households; hence, the result from the current study is not surprising.

As education is believed to improve an individual's reasoning capability as well as increase the awareness of viable technologies to be adopted, the finding that those with a primary school education level are less likely to grow organic crops is explained (Muriithi et al. 2021). Education was also found to be significantly and positively associated with crop rotation strategies, suggesting that the educated decision-maker will try to adopt sustainable agriculture strategies (Mittal and Mehar 2016).

Table 3. Factors influencing decisions to accept ICT-delivered climate change adaption measures.

Dependent Variable	Predictor Variable	B	S.E.	Wald	df	Sig.	Exp. (B)	95% C.I. for EXP(B)	
								Lower	Upper
I grow organic crops	Gender	1.67	0.48	12.02	1	0.00	5.29	2.06	13.56
I grow organic crops	Educational level	−1.64	0.69	5.68	1	0.02	0.19	0.05	0.75
I grow drought-resilient crops	Educational level	−2.55	0.90	8.03	1	0.01	0.08	0.01	0.46

Source: Table by authors.

The second logistic regression conducted was related to the 'growing drought-resilient crops' adaptation activity. The full model containing all predictors was statistically significant, $\chi^2(13, N = 210) = 23.09$, $p = 0.04$. The findings showed educational level to be the only significant predictor of growing drought-resilient crops after receiving climate change messages through ICT. The odds ratio of 0.078 for tertiary educational level was less than 1, indicating that those with primary school education are less likely to grow drought-resilient crops. This finding is similar to the results by Nasim et al. (2019), which suggest that knowledge on cultivation practices is one of the most significant factors that positively correlates with adoption. The finding that tertiary education significantly increases the likelihood of adopting drought-resilient crops after receiving climate change messages through ICT highlights the need to integrate climate education into broader SDG localisation strategies, particularly SDG 4 (Quality Education) and SDG 13 (Climate Action). Limited adoption among those with lower education levels underscores the importance of tailoring ICT-based climate communication to be accessible and actionable for all educational backgrounds (Sapbamrer and Thammachai 2021; Tikon et al. 2023).

4. Conclusions

This study investigated effective pathways of employing ICTs in influencing climate action. Specifically, the research (i) assessed climate change awareness among Shakawe communities; (ii) explored the range of climate change activities undertaken by residents; (iii) examined the sources and communication channels through which climate change messages are disseminated; and (iv) identified the sociodemographic factors influencing the uptake of mitigation and adaptation strategies. Subsequently,

the findings revealed a complex interplay between climate knowledge, information access, and behavioural response, mediated by factors such as education, income, and gender.

In relation to the first objective, this study found a high level of awareness concerning both the causes and effects of climate change. The respondents widely attributed environmental changes—such as limited rainfall, heatwaves, droughts, and season shifts—to climate change. Furthermore, they identified the shift in seasons, drought, and heatwaves as the most pressing threats to their community. These perceptions reflect a nuanced understanding of local climatic variability and its impacts, consistent with the growing body of evidence that climate literacy is rising in African rural communities exposed to persistent environmental shocks (see Sapbamrer and Thammachai 2021).

In addressing the second objective, a diverse range of adaptation and mitigation strategies were observed among Shakawe residents. About two-thirds of respondents reported growing drought-resilient crops, representing a significant behavioural shift towards climate-resilient agriculture. Additional climate actions included the selective harvesting of dry and stipulated types of wood, the household conservation of electricity and water, craft weaving using recycled materials, tree planting, and the adoption of solar energy technologies. These initiatives suggest that local communities are engaging in both individual and collective actions to cope with climate risks, aligning with SDG 13 (Climate Action) and other sustainability goals such as SDG 12 (Responsible Consumption and Production).

In response to the third objective, this study revealed that residents accessed climate information from a variety of sources, with the government being the most cited and trusted entity, followed by local journalists and scientists. Multiple communication channels were utilised, including traditional media (radio, TV, newspapers) and digital platforms (SMS, social media, online news). Despite this, discrepancies emerged between the preferred channels of message sources and end-users, raising concerns about the efficiency of climate communication strategies. Moreover, ICT access was shown to be shaped by economic constraints, further influencing the reach and effectiveness of climate messaging.

Finally, concerning the fourth objective, this study identified income and gender as the most significant predictors of mitigation behaviour, particularly actions involving resource conservation. Notably, gender and educational level emerged as key determinants of adaptation strategies, such as the adoption of organic farming practices. Crucially, the findings demonstrated that educational attainment was the only significant predictor of growing drought-resilient crops

following the receipt of climate messages through ICTs. An odds ratio for tertiary education indicated that individuals with only primary education were significantly less likely to adopt such practices. These findings reinforce the centrality of education in enhancing adaptive capacity and underscore the importance of tailoring ICT-based communication to meet the needs of populations with varying educational backgrounds (see Tikon et al. 2023).

Given these findings, it is safe to state that this study provides empirical evidence that climate change awareness in Shakawe is high and that residents are increasingly engaging in mitigation and adaptation activities. However, the effectiveness of these actions is closely linked to access to tailored information and the influence of sociodemographic factors, particularly education and income. For SDG localisation to be successful in contexts such as Shakawe, climate communication strategies must be inclusive, affordable, and accessible to individuals across all educational levels.

Since this study also found that though climate change communication mostly targets farmers, non-farming activities such as planting trees dominate, it suggests that development stakeholders should 'coordinate their activities and cooperate with each other, diversifying the messages, if climate action is going to become more prevalent' (Tosun 2022). The slanted focus on adaptation, however—not entirely surprising as it is regarded as crucial in the African context—does not cloud mitigation efforts by citizens. The current study further calls for an inclusive climate change communication strategy targeting all sectors, i.e., energy, fashion, tourism, transport, and health, among others, who need to play their part effectively in delivering climate change messages that can influence climate action.

Once achieved, rural communities will be adequately informed to comprehend why they should (i) conserve water and electricity in the context of climate change, (ii) opt for bio-gas energy as opposed to fossil fuel energy, (iii) buy less clothes, (iv) consider climate change-friendly diets, and (v) consider stopping the use of firewood for cooking, among other adaptation and mitigation strategies. Thus, stigmas and perceptions surrounding cycling, an activity associated with poverty, and the use of solar energy, a choice mostly linked with rural farmers, will be eliminated, ensuring that citizens mitigate and adapt substantially.

Without diverse climate change messages from all sectors, people will find it difficult to be resilient, climate change awareness will remain unsatisfactory, while climate action will continue to be limited. Thus, the country will fail to achieve the four dimensions of sustainable development. Holistic inclusivity and participation, as stressed by this chapter's theoretical framework—the Normative Integrated Structural and Participatory Model for Climate Change Communication

(SPCCC), is therefore key if Botswana is going to emerge victorious in the climate fight and improve its Sustainable Development Goal (SDG) Index score which currently stands at 62.7/100 (Sachs et al. 2023).

5. Study Limitations

This study is subject to two key limitations. First, its focus on a single village—Shakawe—restricts the generalisability of the findings to the broader Okavango Delta region. To strengthen the external validity of these results, future research should replicate this study in additional villages within the delta. Second, the timing of the data collection posed a potential limitation. Conducting interviews during daytime hours may have excluded working adults, particularly primary income earners employed within or outside the village. To mitigate this issue, follow-up visits were conducted where necessary, and interviews were rescheduled at times convenient to participants to ensure broader household representation.

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Understanding Climate Action Perceptions in the Caribbean: Harnessing Machine Learning Insights

Letetia M. Addison, Trevon Tewari, Sabina Gooljar and Patrick Hosein

1. Introduction

The Caribbean region, encompassing several Small Island Developing States (SIDS), is widely recognised as one of the most vulnerable regions to be impacted by climate change (Nurse et al. 2014). This vulnerability stems, primarily, from its geographical location which makes it especially sensitive to climate-related events (Taylor et al. 2012). The region experiences a distinct rainfall season from May to November and a dry season from December to April (Taylor et al. 2012; Taylor et al. 2002). In addition, the Caribbean is affected by factors such as the Inter-Tropical Convergence Zone, Easterly Trade Winds, Cold Fronts and is typically in the path of hurricanes and tropical depressions. The Caribbean continues to face natural disasters similar to Hurricanes Irma and Maria in 2017.

Since 1950, the region has been disproportionately affected by such disasters, resulting in substantial loss of life and economic damage. Note that the ratio of coast length to land mass is larger for smaller countries which tend to have fewer reserved resources because of their size. Despite variations across the twenty-six (26) island territories (see Figure 1), certain key features are shared, such as the size of land masses, terrains, and the heavy reliance on coastlines for various socio-economic activities, particularly tourism. Furthermore, the agricultural sector, which contributes 10–35% of the entire region's GDP, is significantly impacted by these events (Karmalkar et al. 2013).

The challenges posed by climate change in the Caribbean are substantial, exacerbated by the unique vulnerabilities of the region. Large coastal populations and exposed geographical locations make the Caribbean particularly susceptible to rising sea levels, intensified storms, increased rainfall leading to flooding, dangerously high temperatures, and shifting precipitation patterns, all of which significantly affect agriculture and water resources. Furthermore, some islands face the alarming prospect of becoming uninhabitable without prompt action.

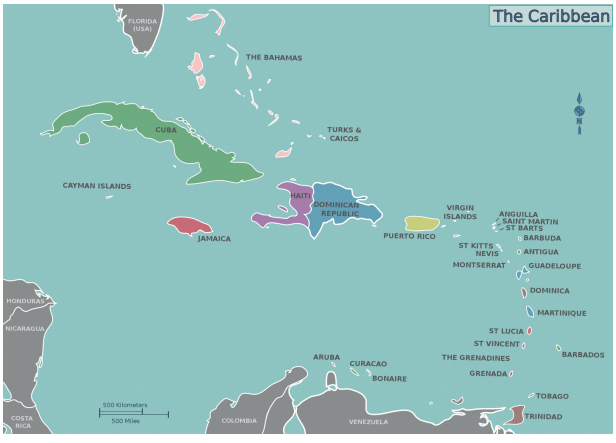


Figure 1. The geographical locations of the 26 Caribbean Islands; the 13 highlighted territories are independent. Source: Reprinted from Wikimedia Commons (n.d.).

In response to these challenges, numerous initiatives by various organisations have emerged to address climate change impacts in the Caribbean. Countries like Barbados and Dominica have taken the lead with ambitious plans to reduce greenhouse gas emissions and invest in climate-resilient infrastructure projects. However, despite these efforts, the region requires substantial support to effectively tackle climate change and build resilience.

In order for governments to prioritise these initiatives, one must educate the population so that they can assist in making the necessary changes. In this process, collecting public perceptions about climate change in the Caribbean is crucial. Continuous understanding of how individuals perceive and respond to climate change can inform policymakers and stakeholders in developing effective strategies to mitigate its effects and build resilience. Continuous feedback is vital to ensure that the actions being taken are indeed resulting in positive change.

Historically, the Caribbean has experienced annual losses owing to hurricane damages equivalent to 17% of its GDP (UNDP 2022). Given the Caribbean's history of environmental challenges and caused by hurricanes, it is likely that public perceptions are deeply influenced by first-hand experiences with extreme weather events. Individuals may express concerns about the increasing frequency and severity of storms, as well as their impacts on lives, livelihoods, and the economy.

Moreover, public perceptions may also reflect awareness of the region's limited contribution to global greenhouse gas emissions compared to its disproportionate vulnerability to climate change. There may be frustration or urgency regarding the need for international cooperation and support to address climate-related challenges.

Furthermore, public perceptions may highlight the importance of preserving and protecting natural resources, such as coastal ecosystems, which play a critical role in buffering against the impacts of climate change, including storm surge and sea-level rise.

In collecting public perceptions about climate change in the Caribbean, researchers and policymakers should consider diverse perspectives across socio-economic, cultural, and geographical contexts within the region. Engaging with local communities, stakeholders, and indigenous knowledge holders can provide valuable insights into adaptation strategies, traditional practices, and community resilience efforts.

While research has primarily focused on the biophysical and chemical effects of climate change in the Caribbean, such as rising sea levels, ocean acidification, and temperatures, there is a gap in the understanding of socio-economic impacts (Eakin et al. 2010; Pike 2013; Canning-Clode et al. 2011). There is a need for more comprehensive approaches to grasp the causes, potential effects, and mitigation methods of climate change (Rhiney 2015).

Advancements in computing, particularly in Big Data, Artificial Intelligence (AI), and Machine Learning (ML), offer promising avenues for addressing complex climate change issues (Bochenek and Ustrnul 2022). ML is a subset of artificial intelligence that enables systems to automatically learn and improve from experience without being explicitly programmed. It involves algorithms that analyse data, identify patterns, and make predictions or decisions based on that analysis.

Researchers have been exploring the potential of Machine Learning (ML) in understanding and addressing climate change challenges. Addison et al. (2025) developed an AI-powered risk classification tool for the OECS, highlighting how predictive analytics can enhance disaster preparedness across Caribbean SIDS. Belesova et al. (2021) developed a systematic database of peer-reviewed studies utilising ML methods to assess climate change mitigation and adaptation actions in urban settings. The aim was to inform decision-makers about the impacts of such actions on human health and wellbeing. Beucler et al. (2024) also developed ML models which are robust to climate variations.

In addition, The ML Methods in Climate Prediction Survey (Chen et al. 2023) focused on evaluating the effectiveness of ML in weather forecasting and climate prediction, particularly in improving accuracy and speed in climate modelling. In addition, various studies have utilised supervised and unsupervised ML to identify and classify climate and health-related articles, generating evidence through heat maps and geographical maps to synthesise trends in climate health publications.

These studies collectively demonstrate the growing role of ML in enhancing our understanding of climate dynamics, impacts, and mitigation strategies. This allows for the real-time exploration of climate-related features such as wind, precipitation, and ocean temperatures which are crucial for understanding and predicting extreme events. Although such studies are more prevalent in larger countries with greater data availability, efforts to increase data collection in the Caribbean will allow for similar research but using our unique constraints.

Therefore, the main research questions of this study are as follows:

1. How can Machine Learning be utilised to collect, analyse, and comprehend public attitudes and perceptions towards climate action in the Caribbean region?
2. What is a suitable framework for a dynamic feedback loop in which the impact of the decisions made based on these data can be measured and used to continuously update the actions taken?

Firstly, recent studies performed on climate perceptions will be reviewed as well as how ML concepts have been applied in the Caribbean context of climate change. From this, a proposed framework will be presented to collate and analyse multiple data sources on climate attitudes obtained from social media, surveys, and public discourse. The framework should demonstrate the potential for applying these Machine Learning techniques to uncover nuanced and comprehensive insights into the factors influencing climate attitudes and the gaps between knowledge and action. Finally, the implications and recommendations of using Machine Learning for designing effective communication and policy interventions that resonate with Caribbean communities will be discussed.

This study aims to provide a novel and interdisciplinary perspective on the use of Machine Learning for climate attitude analysis in the Caribbean region, showcase the advantages and challenges of Machine Learning for capturing the diversity and complexity of climate attitudes across different data sources and dimensions, and offer practical and evidence-based suggestions for enhancing public engagement and participation in climate action in the Caribbean region.

2. Conventional Climate Action Strategies in the Caribbean

Conventional climate mitigation strategies usually align with various approaches, from data collection, data analysis, and dissemination to stakeholders and the public. In the realm of conventional methods employed for gaining climate insights, a variety of approaches are commonly employed. These include face-to-face surveys using closed questions, semi-structured interviews with subsequent thematic analysis, and traditional surveys. Statistical tests are frequently conducted on survey

data to derive meaningful conclusions. In addition, insights are gleaned through interviews, observations, and the analysis of pertinent documents.

Policy analysis, literature reviews, and comparative analyses are also integral methods used to inform climate understanding. Meteorological data, alongside databases such as the Rio climate markers database, provide valuable quantitative information. Additionally, focus group discussions serve as a platform for gathering qualitative insights from diverse perspectives. Together, these conventional methods offer a comprehensive approach to understanding and addressing climate-related challenges (Figure 2).

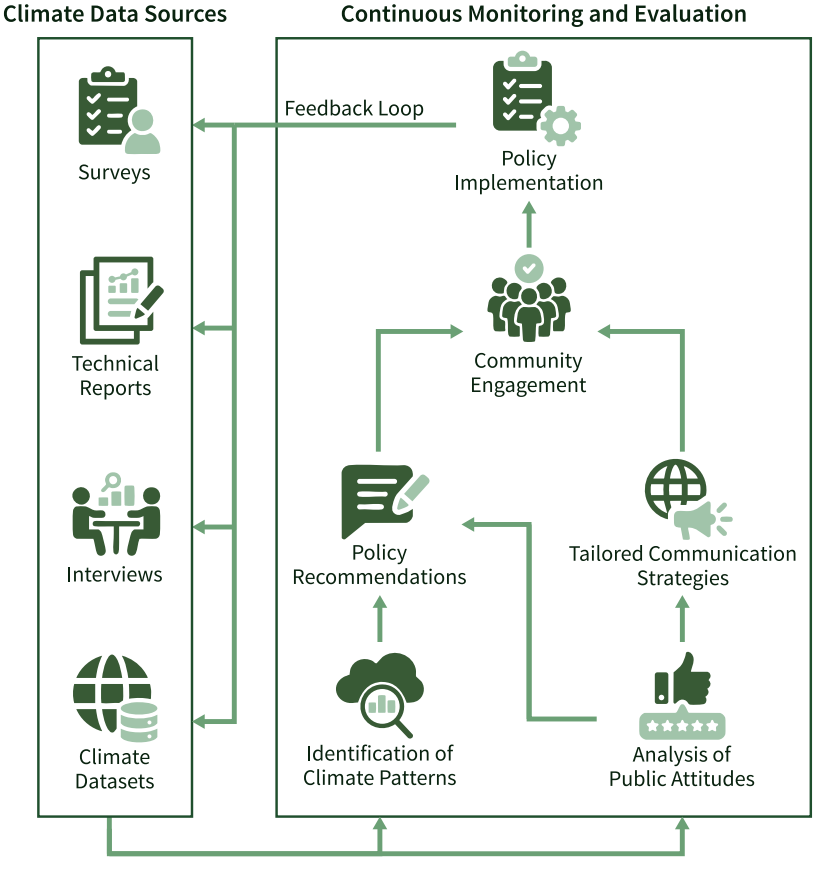


Figure 2. Graphical representation of conventional approaches to climate insights with monitoring and evaluation. Source: Figure by authors; icons sourced from Adobe Stock (n.d.).

2.1. Cases for Conventional Approaches—A Closer Look

Where primary data collection was involved, climate perception data collection tended to revolve around traditional methods such as conducting surveys (Stancioff et al. 2018; Drewry et al. 2022; Whittaker and Bell 2019) and interviews (Dookie et al. 2023; Cloos et al. 2023; Selby et al. 2020) across SIDS. Semi-structured interviews were also conducted with experts in the arena (Robinson 2018) in order to gain insights from policymakers. Secondary data collection methods involved techniques such as keyword searches on Google Scholar followed by manual review for relevance (Bochenek and Ustrnul 2022) as well as consultation of government and civil society documents and reports, scholarly books, and articles (Montoute et al. 2019).

2.1.1. Thematic Analysis

Thematic analysis was applied to the interviews revolving around climate perception data usage (Dookie et al. 2023; Mahon et al. 2021) to extract ideas based on the opinions gathered. With respect to more quantitative data, some studies such as those by Dookie and Spence-Hemmings (2022) established metrics based on historical observational data to quantify features such as storm awareness timing to determine an island's preparedness in the event of alerts. Lewis and Su (2021) also investigated metrics such as a policy coherence score which quantifies the measure of coherence of some SIDS territories to that of the climate change adaptation policies outlined for them.

2.1.2. Surveys

Whittaker and Bell (2019) conducted a survey in St. Kitts and Nevis, involving 228 residents aged 15–75 years between 2015 and 2017. Results showed that 88.6% of respondents were aware of climate change, while 43.2% felt personally unprepared for its consequences. About 35% were unaware of government measures to enhance adaptive capability, but half were willing to invest in such measures. Top solutions proposed by residents for improving future resilience included education and awareness programmes, sustainable land use development, and renewable energy. Similarly to findings by Drewry et al. (2022), respondents primarily obtained climate change information from television (62%), the internet (62.4%), and radio (43.7%).

2.1.3. Semi-Structured Interviews

Dookie et al. (2023), Cloos et al. (2023), Selby et al. (2020), and Robinson (2018) utilised semi-structured interviews to explore climate action perceptions in

the Caribbean. Dookie et al. (2023) focused on climate information utilisation in the region, conducting 26 interviews with sectoral experts. Results revealed challenges and facilitators to decision-making using climate knowledge. While 12 out of 26 respondents utilised such information, concerns were raised about the lack of formal definitions, the politicisation of resilience, and shifting goalposts. The study identified barriers to using climate information, including application/usability issues, limited awareness and access, political and policy challenges, and resource constraints. Enablers for improved utilisation included better contextual relevance, application and training, increased awareness and access, and recent events. Financial factors, donor attention, and international drives were highlighted as preferred factors driving demand for climate information.

Cloos et al. (2023) investigated human mobility experiences in Dominica after extreme weather events (tropical storms or hurricanes), with an emphasis on material and living situations, access to resources and support, social network conditions, and health concerns. Thus, interviews were conducted with 25 people who were internally displaced following an extreme climate event in Dominica and with people who migrated from Dominica to Guadeloupe. Participants' health assessments varied, with 13 viewing their health positively and 11 negatively. The study highlighted significant mental health challenges like panic, worry, and stress, especially among those displaced and lacking proper shelter during the crisis.

Financial losses were substantial, leading many to depend on aid from international organisations and their families. The importance of community support post-disaster was emphasised, though some noted community divisions. Housing, food, water, and adapting to new environments posed challenges, with uneven support and issues adjusting to urban life. Access to essential services, including healthcare and psychosocial support, was inconsistent across areas. Displacement to places like Guadeloupe was influenced by immediate post-disaster conditions and existing socio-economic connections, with some citing improved healthcare access as a factor for relocation.

Selby et al. (2020) explored climate change learning initiatives in St. Vincent and the Grenadines, critically reviewed leading-edge approaches to climate change education, and considered implications for re-conceptualising "good practice" in climate change education. As such, their findings revealed that a blend of formal and informal learning is effective, activism is woven into both learning contexts, and trans-disciplinary learning transcends disciplinary boundaries.

Moreover, Robinson (2018) identified trends and limitations in how SIDS in the Caribbean region are adapting to climate change at the national level from 26

Caribbean policymakers from Antigua and Barbuda, Belize, Dominica, Guyana, Jamaica, St. Lucia, and Trinidad and Tobago. Findings showed that these islands are actively pursuing climate change adaptation through vulnerability assessments, public education, and policy development, with sea-level rise identified as a critical concern.

Key climate-induced vulnerabilities addressed include hurricanes, storm surges, rainfall, temperature changes, and drought, alongside non-climate issues like economic constraints and social factors. It was also highlighted that adaptation efforts prioritise sectors such as coastal zones, forestry, agriculture, tourism, and water. Jamaica was noted for establishing a dedicated Climate Change Division, with sea-level rise identified as a major climate impact. However, although there are proactive measures, challenges to adaptation exist, including financial limitations, technical capacity, and governance issues.

2.1.4. Mixed-Method Approaches

In general, mixed-method approaches were found to be most popular and are justified by the combined insights gained from both qualitative and quantitative data. Drewry et al. (2022) conducted an online survey on 2599 individuals from ten English-speaking Caribbean nations to assess public perceptions on climate change and health. The study aimed to inform climate and health communication plans, establish a baseline for tracking public understanding and engagement, address the lack of region-specific data, and promote further research.

Results showed that the majority of respondents (60%) believed that human actions are the main cause of climate change, with many seeing it as having a moderate to significant impact on health, mainly due to extreme weather, heat, and air pollution. Most respondents (84%) recognised vulnerable populations affected by climate change and felt that their countries should intensify efforts to protect citizens from climate-related health issues. They also expressed trust in Ministry of Health officials and local healthcare providers over traditional news outlets and social media for climate change information.

Overall, we find that conventional climate change education in Caribbean countries benefits from innovative, community-driven approaches, which can inform global best practices.

3. Critical Themes Derived from Climate Action Strategies

Using the insights from conventional approaches for understanding climate action perceptions in the Caribbean, we can explore innovative strategies that

address specific demands within key sectors. For instance, the specific demand for climate services in the tourism sector highlights a gap in tailored climate information services, essential for informed decision-making within particular industries (Mahon et al. 2021). By examining themes such as community engagement and education, sustainability, technological innovation, environmental justice, and policy coherence, these insights can be tailored into climate change adaptation strategies for informed decision-making and sustainable development in the Caribbean.

3.1. Community Engagement and Education

Community engagement and education are increasingly recognised as foundational in strengthening resilience to climate change. Investigations into local perceptions, such as those conducted in St. Kitts and Malé, Maldives, underscore the importance of incorporating local knowledge into climate change adaptation strategies (Stancioff et al. 2018). Furthermore, the potential of merging formal and informal learning strategies is highlighted in initiatives aimed at enhancing community awareness and action against climate change (Selby et al. 2020). The breadth of community-led actions in addressing the health impacts of climate change in the Anglophone Caribbean calls for further research to innovate adaptation and health strategies, advocating for community-centric approaches in climate change education and action (Myhre et al. 2024).

3.2. Sustainability, Technological Innovation, and Environmental Justice

The nexus of sustainability, technology, and environmental justice offers insightful perspectives on the multifaceted challenges and opportunities presented by climate change. The use of artificial intelligence (AI) applications in addressing sustainability challenges within Latin America and the Caribbean showcases the promising role of technology in advancing sustainable development and environmental issue mitigation (Salas et al. 2022). In addition, the social dimensions of environmental risks, particularly flood injustice, spotlight the uneven impacts of environmental hazards across communities and the role of policy in these disparities, advocating for a focus on environmental justice in climate adaptation policymaking (Sullivan et al. n.d.).

3.3. Policy Coherence and Adaptation Strategy Integration

Integrating climate change adaptation into sectoral and national policies is crucial for a coordinated and effective response to climate change. Studies examining policy coherence and adaptation strategies within the Caribbean reveal challenges in

aligning sectoral policies with national adaptation goals (Lewis and Su 2021). These challenges highlight the need for enhanced policy coherence to facilitate cohesive and effective adaptation planning and implementation, pointing to financing, institutional arrangements, and political will as key barriers (Robinson 2018).

4. Applying Machine Learning Approaches for Climate Action Strategies

In the Caribbean region, Machine Learning and AI can play a pivotal role in enhancing knowledge, attitudes, and perceptions. The application of these advanced methodologies in climate change research has resulted in improved weather predictions with increased warning periods. This integration is crucial for refining climate models and forecasts, with studies emphasising the role of Machine Learning in increasing the precision of weather and climate modelling (Bochenek and Ustrnul 2022).

The significance of disseminating timely storm alerts and warnings is paramount in disaster preparedness efforts. Research indicates notable variability in storm awareness times across the Caribbean, underscoring the necessity for enhanced communication strategies to facilitate the efficient dissemination of critical risk information (Dookie and Spence-Hemmings 2022).

4.1. Customised Climate Information

Machine Learning models offer the capability to analyse historical climate data specific to the Caribbean, yielding tailored insights. By comprehending local climate patterns, communities can make well-informed decisions regarding adaptation and mitigation strategies. These models also facilitate predictions on various aspects of climate change. For instance, Nichols and Hosein (Nichols and Hosein 2021) introduced a computationally cost-effective solution using ensemble ML methods for deforestation prediction in Small Island Developing States (SIDS). This approach proves more accessible to SIDS due to lower resource requirements compared to Fully Convolutional Neural Networks (FCNs). Since updated satellite data are often unavailable for SIDS, the models fill a critical gap by allowing these territories to monitor deforestation rates using less intensive resources, despite the challenges of data collection and satellite coverage peculiar to their location.

As shown by Kemp (2024), internet access and social media usage in Trinidad and Tobago in 2023 stood at 79% and 65.5%, respectively, with 82.9% of internet users using at least one social media platform. These statistics indicate that social media networks can serve as media for disseminating updates on weather events or natural disasters in SIDs. The reach of these networks allows for user-based reporting, giving

communities access to more real time information, at the risk of its validity. Given the pervasiveness of social networks in modern times, they have been viewed with much attention for the potential in the information that can be extracted and used.

One such method is shown to capitalise on this information from tweets. Hernandez-Suarez et al. (2019) presented a method where Twitter data were leveraged to depict areas in which a majority of tweets reporting natural disasters are concentrated. A case study was performed using Mexico's 2017 earthquake and showed that the resulting coordinates obtained coincided with the data presented by the federal government of Mexico. Applications such as this enhance the current state of climate information dissemination, offering real-time updates with verification through the use of majority reporting.

4.2. Early Warning Systems

Machine Learning algorithms have the capability to forecast extreme weather events, such as hurricanes and floods, with increased precision. By providing advanced warnings, these predictions enable governments and citizens to take proactive measures, thereby protecting lives and property from potential harm. Such timely actions can significantly mitigate the impact of these hazardous events, ensuring the safety and wellbeing of affected communities. Studies suggest that the benefits of these Early Warning Systems greatly exceed their costs (Bouwer et al. 2014).

In order to implement a given Early Warning System, several factors must be addressed. Firstly, significant knowledge of the disaster at hand must be gathered. Features such as the hazards, exposure, vulnerabilities and risks associated with the event must be identified to allow for the best decisions to be made. Data such as historical events, geography, environmental aspects, and economic aspects, to name a few, should be collated and analysed to gain prior insight into the decisions to be made and their potential effects (Acosta-Coll et al. 2018).

Secondly, forecasting methods are key in identifying the real-time causes for concern. This usually exists under two sections. The first is Monitoring and is responsible for gathering data regarding the necessary variables associated with the particular event. The second refers to the Information Processing Unit and deals with analysis and modelling based on the data supplied by the Monitoring Unit (Acosta-Coll et al. 2018). Visualisations based on the results here are typically used to support timely decisions from the requisite authorities as well as citizens (Weichselgartner and Pigeon 2015).

Thirdly, the content of alerts as well as the media by which transmission of these alerts to the general public should be considered, allowing the affected population

adequate time to make educated decisions. Considerations such as the reach of the alerts, as well as the understanding of the alerts sent, should also be researched to provide quick and clear facts to the public (Acosta-Coll et al. 2018).

Finally, disaster preparedness is concerned with allowing the population to be able to react when an event occurs (Altay and Green 2006). The population must be able to interpret the alerts issued to be able to make fast, effective decisions based on their respective situations. Protective measures should be taken by potentially affected communities based on the communicated information (Acosta-Coll et al. 2018).

4.3. Climate Education and Awareness Using Machine Learning

Climate education and awareness can be significantly enhanced through the utilisation of Machine Learning (ML). ML-powered educational tools have the capacity to effectively disseminate climate knowledge to a wide audience. Interactive platforms, chatbots, and mobile applications powered by Machine Learning algorithms can engage citizens in meaningful ways, fostering awareness and deepening understanding of climate-related issues. These innovative tools provide an interactive and accessible means for individuals to learn about climate change, its impacts, and potential solutions, thereby empowering them to take informed actions towards environmental sustainability.

Natural Language Processing (NLP) and Large Language Models (LLMs) can revolutionise climate education and awareness by leveraging their capabilities to analyse, generate, and understand human language. Firstly, NLP algorithms can sift through vast amounts of textual data related to climate science, policy documents, research papers, and educational materials to extract key insights and trends. These insights can then be used to tailor educational content and create informative resources that cater to different learning styles and preferences.

Sentiment analysis, an area of study in the field of NLP, is a technique that summarises the overall sentiment of textual data. Sentiment analysis categorises sentiments as positive, negative, or neutral which can unearth the general public's attitudes toward climate action. Sentiment analysis emerges as a pivotal technique in the realm of NLP, particularly within the context of the climate change discourse.

Findings from Krishnan and Anoop (2023) highlight the application of ClimateBERT for sentiment analysis in the climate change domain. It is clear that such techniques offer a powerful means to enhance climate education and awareness. Their work demonstrates sentiment analysis as a pivotal tool in deciphering the complex tapestry of public opinion on climate change which showcases its utility in gauging sentiments across a spectrum of discussions from social media to news

articles. This depth of insight allows for the nuanced tailoring of educational content to meet the audience's specific needs and concerns.

By identifying prevalent sentiments, whether they are concerns, misconceptions, or areas of particular interest, climate education initiatives can adapt to more effectively communicate crucial information. For example, detecting a strong interest in sustainable technologies could lead to the development of specialised content that explores innovative solutions in detail, thereby feeding the audience's curiosity and fostering a deeper understanding. Similarly, pinpointing areas of scepticism or misinformation enables educators to directly address these issues. Hence, providing clear, fact-based responses thus enhances the overall educational impact.

Topic modelling is another area of NLP that can be used in climate change awareness and education. Topic modelling techniques categorises a corpus of text data into distinct themes such as renewable energy, conservation efforts, and policy support. By applying Latent Dirichlet Allocation (LDA), researchers can identify underlying themes in discussions on climate change, offering a structured overview of public sentiment and discourse patterns. This organisation of data not only facilitates a deeper comprehension of the public's concerns and interests but also aids in identifying areas requiring further education or policy intervention (Uthirapathy and Sandanam 2023).

In addition, LLMs, such as OpenAI's GPT series, can generate natural language text that mimics human-like writing. This capability can be harnessed to develop interactive educational materials, such as chatbots or virtual assistants, that engage users in meaningful conversations about climate change. These chatbots can provide personalised responses to users' queries, offer explanations of complex concepts in simple terms, and even simulate real-world scenarios to enhance learning experiences.

Furthermore, NLP and LLMs can facilitate the translation of climate-related information into multiple languages, thereby extending the reach of climate education initiatives to diverse communities worldwide. By breaking down language barriers, these technologies enable a more inclusive approach to climate education and awareness, ensuring that individuals from all backgrounds have access to valuable information and resources.

As observed across several studies (Dookie et al. 2023; Selby et al. 2020; Salas et al. 2022), document analysis, literature reviews, and semi-structured interviews are prominent in gaining insights into climate information use as the data available are qualitative in nature. As a result, techniques such as thematic analysis and deductive coding must be applied to extract key information from these data collection practices.

In recent times, LLMs have been made publicly available such as OpenAI's Chat Generative Pre-trained Transformer (ChatGPT).

There are artificial intelligence (AI) models derived from deep learning techniques and these are used to generate text (Dengel et al. 2023). LLMs can be employed to streamline the processing of documents and interview exchanges, extracting essential points and themes, instead of depending on manual thematic analysis. Such technologies can efficiently manage large documents, handling analyses that may be time-consuming even for domain experts. They can also be used to automate the conducting of surveys by simplification of the survey conducting process (Tewari and Hosein 2024).

Chew et al. (2023) reported that their findings in testing LLMs for deductive coding were comparable to that of human coders and promoted the use of LLMs as an assistive tool to support larger qualitative research where manually taxing tasks are concerned. De Paoli (2023) looked into the use of LLMs in performing thematic analysis in semi-structured interviews and found that the models could identify most of the main themes from previous research with a good degree of validity. This means that these solutions provide a gateway into accelerated climate information insights from longer-form data, thereby enriching the availability of qualitative climate information and policies.

Overall, the integration of NLP and LLMs into climate education and awareness efforts holds immense potential to enhance learning experiences, foster engagement, and empower individuals to take meaningful action towards addressing climate change.

4.4. Behavioural Change Interventions and Local Adaptation Strategies

Machine Learning can identify patterns in human behaviour associated with climate change, offering valuable insights into the factors influencing environmental actions. By analysing data from various sources, ML algorithms can pinpoint trends and preferences related to sustainability practices. These insights enable targeted interventions aimed at encouraging behaviours that contribute to environmental conservation, such as reducing energy consumption or adopting eco-friendly transportation methods.

For instance, Machine Learning can be used to analyse transportation data from mobile apps and public transit systems. The analysis can reveal patterns of commuting behaviour, including peak travel times and preferred modes of transportation. Based on these findings, government planners can implement targeted interventions, such as incentivizing public transit use during peak hours

and promoting bicycle-sharing programmes, similar to those in developed countries where there is a noticeable decrease in carbon emissions and traffic congestion, demonstrating the effectiveness of ML-driven interventions in promoting sustainable transportation practices.

4.5. Enhanced Climate Action Using Machine Learning

Machine Learning enhances climate models by integrating regional data, refining them to offer more precise projections. These fine-tuned models are invaluable for policymakers and planners, providing them with enhanced accuracy to make informed decisions regarding climate-related issues. This process is shown in the graphical representation in Figure 3.

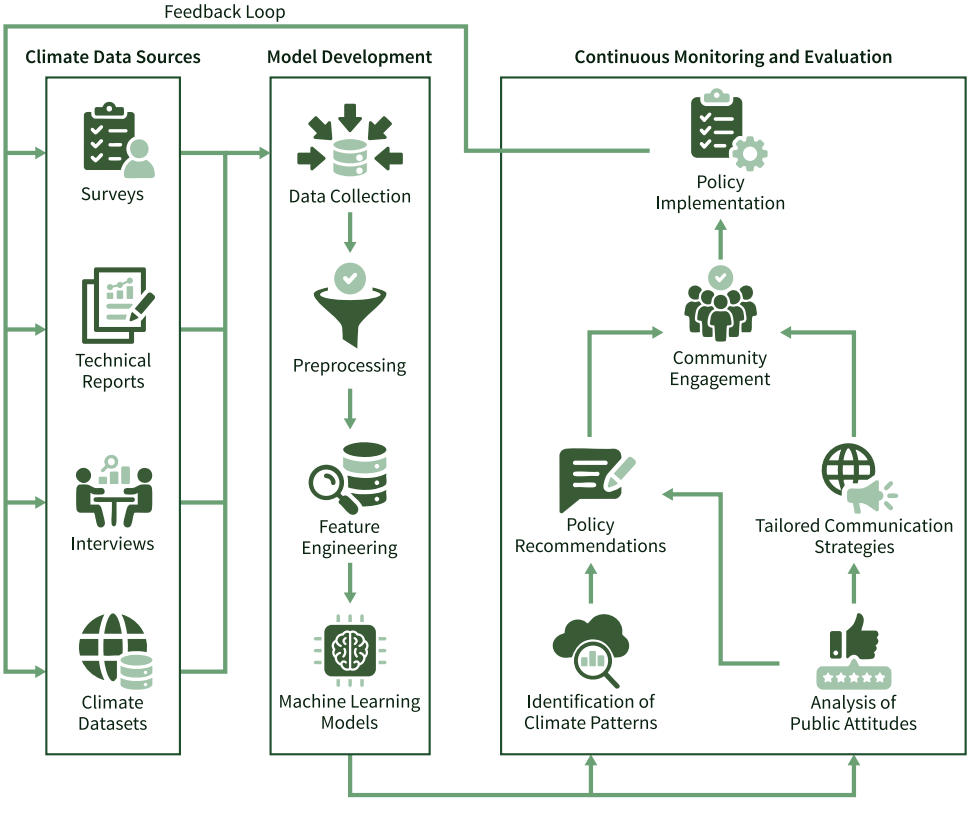


Figure 3. A graphical representation of the continuous feedback loop which incorporates Machine Learning to enhance conventional climate action approaches. Source: Figure by authors; icons sourced from Adobe Stock (n.d.).

Data collection involves gathering diverse datasets from the Caribbean region, including social media posts, survey responses, news articles, climate data, and government reports. In February 2025, there were 2.03 million cellular mobile connections among a population of 1.51 million, with 1.28 million individual internet connections and 873 thousand social media identities in Trinidad and Tobago (DataReportal 2025). To best perform data collection among populations with varying levels of access to telecommunications infrastructure, a multi-tiered data collection approach may be necessary. In the first tier, social media data can be used to capture a large portion of the population. Where social media usage may not be sufficient, mobile phone surveys can be utilised.

Given the widespread presence of mobile phone usage across the Caribbean, mobile phone surveys remain prevalent in both high- and low-income countries, especially in low-income countries due to limited landline, internet, and personal computing infrastructure (Gourlay et al. 2021). Where mobile phone surveys may not be sufficient, in-person surveys can be conducted in disaster-prone areas or communities recently affected by disasters. This approach ensures that social media data are not assumed to represent the entire population, and persons with various levels of technological access are adequately accounted for.

Once collected, the data undergo preprocessing to remove noise, handle missing values, and standardise data formats. Traditionally, datasets were processed using various methods such as document analysis and thematic analysis in the case of qualitative data and the use of statistical methods in the case of quantitative data to build appropriate models for analysis.

However, with the advancement of Machine Learning, these models can be trained using the pre-processed data to analyse public attitudes, climate patterns, and their interconnections. Feature engineering can extract relevant features like sentiment scores, climate indicators, demographic information, and geographic location. Sentiment analysis and topic modelling can analyse public perceptions towards climate action and resilience efforts. Machine Learning algorithms can also analyse climate data and identify patterns, trends, and potential climate-related risks in the Caribbean region.

It is also important to note that most statistical models, in particular, focus on inference rather than the predictive ability of Machine Learning models (Bzdok et al. 2018). These methods are still important, as not all of these datasets meet the requirements for training a Machine Learning model and so many potential insights are potentially neglected due to the focus on inference. Qualitative analysis

techniques such as deductive coding are often time-consuming exercises (Beucler et al. 2024) and can be accelerated using LLMs as in the aforementioned research.

Figure 3 highlights the traditional route, without the use of Machine Learning models. However, the feedback loop represents a non-continuous process, as re-performing the conventional analyses with added data proves more time consuming especially when compared to the ease of retraining a Machine Learning model. However, a combination of both the traditional and modern approaches may offer the most benefit to these systems due to the differences in focus, this being inference for statistical models and prediction for Machine Learning models. It should be noted that qualitative Machine Learning solutions are not yet at the level to completely replace the traditional methods but can definitely be used to augment and accelerate the process.

Insights derived from Machine Learning analysis inform policymakers about public sentiments, climate vulnerabilities, and effective strategies for climate resilience. Tailored communication strategies are developed based on identified public attitudes and concerns to raise awareness and promote climate resilience measures. Community engagement plays a crucial role in sharing knowledge, providing education, and encouraging participation in climate resilience initiatives. Implemented policies and interventions are continuously monitored for effectiveness, with a near real-time, dynamic feedback loop informing future data collection, model refinement, and policy adjustments. This dynamic and adaptive approach ensures continuous improvement in climate resilience efforts.

4.6. Machine Learning Methodology and Agent-Based Extensions

In this study, we apply a structured machine learning (ML) framework tailored to analysing public climate perceptions and attitudes in the Caribbean. This methodology combines supervised and unsupervised learning techniques with recent advances in natural language processing (NLP) and Large Language Models (LLMs), all within a feedback-based agent architecture.

Supervised learning methods, such as decision trees and ensemble models, are used for classification tasks involving sentiment and perception data derived from structured surveys and labelled social media datasets. As shown by Bochenek and Ustrnul (2022), such algorithms are effective for analysing weather and climate data due to their ability to manage heterogeneous and noisy inputs, which is highly relevant for regional data from Small Island Developing States.

In cases involving unlabelled or text-heavy datasets, such as public discourse from social media or interview transcripts, unsupervised techniques are deployed.

Topic modelling techniques, like Latent Dirichlet Allocation (LDA), have already been employed in similar contexts to identify emerging themes and dominant public concerns related to climate change (Uthirapathy and Sandanam 2023).

To enhance these processes, we propose the integration of Large Language Models (LLMs) such as GPT-type models, which have demonstrated effectiveness in document summarization, thematic analysis, and deductive coding tasks (Chew et al. 2023; De Paoli 2023). For instance, Chew et al. (2023) reported that LLMs achieved comparable results to human coders in deductive coding, and De Paoli (2023) found LLMs capable of identifying key thematic structures in qualitative interview data with acceptable validity.

The methodology also incorporates autonomous agents designed to function as intermediaries in a continuous feedback loop between data sources and policymaking. These agents use ML model outputs to recommend adaptive communication strategies, tailor educational interventions, and update system parameters in real time based on incoming data. This dynamic loop approach builds on the hybrid framework already proposed in this study (see Figure 3), which combines conventional thematic analysis with retrainable ML models for efficiency and scalability.

Given the linguistic diversity across the Caribbean, particularly the use of English Creole and other dialects, the deployment of NLP systems must also involve culturally adapted preprocessing. Previous work, such as the application of *ClimateBERT* in climate sentiment analysis (Krishnan and Anoop 2023), highlights how models trained on domain-specific data can significantly improve the accuracy of public opinion tracking and thematic extraction in climate discourse.

By leveraging these modern techniques, our ML methodology not only enhances the speed and depth of analysis but also provides a scalable infrastructure that integrates traditional qualitative methods with advanced computational models. This hybrid system is intended to inform a more responsive, inclusive, and data-driven approach to climate policy and education across Caribbean SIDS.

This study primarily adopts an explanatory approach to ML, aiming to uncover patterns, themes, and influencing factors behind climate attitudes in the Caribbean. While some predictive elements—such as sentiment classification and risk forecasting—are used, the core objective is to interpret public perceptions and inform targeted interventions. Predictive accuracy is therefore secondary to interpretability, cultural relevance, and the practical utility of insights for stakeholders and policymakers.

5. Discussion

In order to truly assess the potential of Machine Learning techniques in analysing public attitudes and perceptions towards climate action in the Caribbean, it is important to examine the applicability of these algorithms, the challenges they pose, and the implications for policy and communication strategies. The unique challenges in the Caribbean allow for the application of a variety of Machine Learning techniques suitable for studying climate attitudes in the Caribbean. Techniques like sentiment analysis, natural language processing, and clustering algorithms show promise in identifying patterns and sentiments within the diverse cultural context of the region.

The effective application of Machine Learning algorithms requires careful consideration of the region's socio-cultural nuances. By utilising diverse data sources such as social media interactions, surveys, and public discourse, these algorithms can uncover insights into public attitudes towards climate action, providing a basis for targeted interventions. However, the use of Machine Learning in this context comes with challenges and limitations. Issues such as data availability and quality, cultural and linguistic differences, and algorithmic biases present significant obstacles. Moreover, the digital divide and varying levels of technological infrastructure across the Caribbean pose challenges to comprehensive data collection.

A critical consideration in applying NLP and ML to analyse public attitudes towards climate change in the Caribbean is the region's rich linguistic and cultural diversity. The Caribbean is home to numerous languages and dialects, such as English Creole and French Creole. Each dialect is embedded with unique cultural nuances that affect communication patterns. To ensure that analyses accurately capture public sentiment and avoid misinterpretation, this study proposes the use of multilingual NLP models, the development of Caribbean-specific language datasets for fine-tuning, dialect-specific preprocessing to account for informal expressions, and embedding local cultural context through curated domain knowledge. In addition, to ensure that the models remain accurate and culturally appropriate, local community members and linguistic experts should regularly review its outputs and provide feedback for continuous improvement. By addressing these challenges proactively, ML insights can more faithfully reflect the diversity of the Caribbean voices and enhance the relevance and impact of climate action strategies

Machine Learning offers valuable tools for advancing climate action efforts, but it comes with drawbacks. Foremost among these is the computational expense, requiring substantial resources in terms of computing power and data. Additionally,

Machine Learning models rely heavily on high-quality data, which can be scarce and biassed in the context of climate science.

In addition, interpretability and transparency issues arise due to the complexity of many Machine Learning algorithms, posing challenges in understanding their decision-making processes. Ensuring the generalisation and robustness of these models to future climate conditions is crucial, as is addressing ethical concerns surrounding their deployment, such as the equitable distribution of benefits and potential reinforcement of biases.

Overcoming these challenges requires interdisciplinary collaboration and active mitigation strategies to leverage Machine Learning effectively in the pursuit of climate resilience and sustainability. Considering the transformative potential of Machine Learning insights on policy interventions and communication strategies, there is potential for more targeted and effective approaches. By aligning policies and communication efforts with prevailing attitudes and perceptions, policymakers can enhance acceptance and engagement, fostering greater community involvement.

Machine Learning insights offer a pathway to bridge the gap between knowledge and action in addressing climate change in the Caribbean. By providing policymakers with actionable insights into public attitudes and perceptions, Machine Learning facilitates evidence-based interventions tailored to the region's unique needs. Through interdisciplinary collaboration and informed decision-making, meaningful action towards climate resilience and sustainability can be catalysed in the Caribbean region.

5.1. Translating ML Insights into Policy Interventions

While Machine Learning techniques enable nuanced understanding of climate perceptions, these insights must be systematically channelled into tangible policy mechanisms. We propose a four-pronged approach for translating data-driven findings into concrete, institutional action.

5.1.1. Institutional Feedback Channels

To ensure the regular integration of insights, analytical outputs should be fed to ministries and government units through established intermediaries. For example, findings can be channelled through national climate focal points or policy liaisons embedded in regional organisations. Ministries such as Planning, Rural Development, or Public Utilities can receive automated sentiment summaries and trend dashboards, updated monthly.

This process should be formalised via collaboration with local operational entities such as the Office of Disaster Preparedness and Management (ODPM) in Trinidad and Tobago, which plays a key role in emergency communication. ODPM and similar agencies can translate model outputs into risk maps, alert thresholds, or climate behaviour prompts, especially in the aftermath of climate-related events.

5.1.2. Role of Regional Climate Institutions

Regional organisations like the Caribbean Institute for Meteorology and Hydrology (CIMH) already play an active role in synthesising and broadcasting climate data across the region. ML-based public perception trends can complement CIMH's climate outlooks by adding a human-centred layer, i.e., how people *feel* and *react* to climate threats. CIMH and similar institutions can act as brokers of both technical and social climate insights, helping disseminate both to government stakeholders and the wider public.

5.1.3. Community-Level Integration via Digital Agents

Tools such as LLM-powered education platforms have already been piloted for flood risk communication in SIDS, offering a pathway for integrating sentiment-informed messaging (Addison et al. 2024). As outlined in Section 4.5, LLM-powered agents can support participatory policy by interacting with citizens in local dialects, gathering structured feedback, and summarising thematic concerns. These agents can be embedded in mobile applications or integrated into local community centres. Their outputs, when verified by experts or civil society monitors, can feed directly into national adaptation strategies, development plans, or resilience-building programmes.

5.2. Ethical Considerations in Machine Learning and Data Collection

The use of public data sources such as social media raises important ethical concerns. Although these platforms are open-access, users may not have explicitly consented to their content being used for research. To address this, all data used should be anonymized and aggregated to protect individual privacy. Bias is another key risk, particularly in NLP models that may misinterpret local dialects or under-represent marginalised voices. To mitigate this, we advocate for fine-tuning models on Caribbean-specific data and involving local experts in review processes.

Large Language Models and digital agents should be implemented with transparency and human oversight to prevent misuse or unintended harm. Ethical use also involves ensuring that communities benefit from the research—such as by

sharing insights with local and regional partners like ODPM or CIMH to support risk communication and resilience planning. A future ethics framework tailored to the Caribbean SIDS context is recommended to guide responsible ML application in climate research.

6. Conclusions and Future Directives

The application of ML insights presents a promising avenue for bridging the gap between knowledge and action in addressing climate change within the Caribbean region. By pinpointing specific knowledge gaps related to climate issues unique to the Caribbean, such as the impacts of hurricanes, sea level rise, and coral reef degradation, Machine Learning can guide targeted educational efforts to raise awareness and enhance understanding among the public.

Moreover, predictive models generated through Machine Learning can anticipate the diverse responses of Caribbean communities to proposed climate policies. This foresight enables policymakers to tailor their strategies to better align with the needs and concerns of the region, ensuring greater acceptance and effectiveness of climate initiatives.

In addition, leveraging Machine Learning to gain insights into the sentiments and priorities of Caribbean communities can inform the development of more engaging and culturally relevant climate action initiatives. By involving local stakeholders and addressing their specific challenges and perspectives, these initiatives can foster a stronger sense of ownership and community involvement in the fight against climate change.

Future work should focus on operationalising the proposed ML framework across more Caribbean territories and using multilingual NLP models tailored to regional dialects and local speech patterns. Longitudinal data collection and panel-style perception surveys could support tracking shifts in climate attitudes over time and help evaluate the long-term effectiveness of educational interventions. Expanding partnerships with agencies like CIMH, ODPM, and local NGOs can also facilitate real-time feedback loops, integrating public sentiment into disaster planning and communication systems.

Building on these foundational directions, recent applied research is already expanding the use of Machine Learning and Large Language Models into new climate resilience domains across SIDS. Ongoing work is demonstrating the utility of Large Language Models (LLMs) in developing digital agents for community-based flood education and real-time alerts in SIDS, highlighting the potential for context-aware AI in disaster risk reduction (Addison et al. 2025). These mechanisms

illustrate the expanding role of Machine Learning and LLMs in advancing public climate communication, localised vulnerability assessment, and climate-adaptive infrastructure planning across SIDS.

Further research should also explore ethical and regulatory frameworks for the use of LLMs in participatory governance, especially in low-resource or linguistically diverse regions. Finally, agent-based modelling of behavioural responses to climate policy—combined with sentiment-driven feedback—may offer valuable foresight for adaptive planning in Caribbean SIDS.

As we harness the potential of technology and innovation, let us remain committed to supporting Caribbean nations in their efforts to build resilience and sustainability in the face of climate challenges. By working together and integrating Machine Learning insights into our approach, we can create a more resilient and prosperous future for the Caribbean and its people.

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Albertha Joseph-Alexander has been a member of the Caribbean Academy of Sciences Trinidad and Tobago Chapter (CAS-TT) since 2021. She previously served, for one year, as the Acting President of the chapter and is now the first female President of the CAS-TT local chapter. Dr. Joseph-Alexander obtained her PhD in Plant Science and an MSc in Crop Protection from The University of the West Indies, St. Augustine Campus. In 2021, she attained a Professional Master's Degree [EE1.1]in the Communication of Science and Innovation from the University of Trento, Italy. Going by the sobriquet DrStoryTell, Dr. Joseph-Alexander aims to use science communication and storytelling as a vehicle to effectively translate research information for the benefit of Caribbean people. In recent years, she has also had the opportunity to be involved in planning the Pigeon Peas Festival and the Mango Festival in collaboration with local NGOs. She appreciates the power of such activities to be 'fun places where facts abound'. Presently, she is producing her first documentary, which is based on pigeon peas, which she studied for her doctorate.

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Patrick Hosein attended the Massachusetts Institute of Technology (MIT), where he obtained five degrees including a PhD in Electrical Engineering and Computer Science. He has worked at Bose Corporation, Bell Laboratories, AT&T Laboratories, Ericsson and Huawei. He has published extensively with over 200 refereed journal and conference publications. He holds 41 granted patents in the areas of telecommunications and wireless technologies. He was nominated for the Ericsson Inventor of the Year award in 2004, was the Huawei US Wireless Research Employee of the year in 2007, was a 2015 Anthony Sabga Caribbean Laureate for Science and Technology, is a National Geographic Explorer, and was a recipient of the Order of the Republic of Trinidad and Tobago (ORTT) award in 2024. Patrick is presently the administrative and technical contact for the TT top level domain, CEO of the TTNIC, and a Professor of Electrical and Computer Engineering (and formerly a Professor of Computer Science) at the University of the West Indies. His present areas of research include Applied Data Science, Operations Research and Performance, and Pricing Optimisation for Cellular Networks.

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and Tanzania. Community-based seed security development is another significant area in which Mr Hossain has worked extensively, especially in eastern India and Bangladesh.

S.M.C.B. Karalliyadda

S.M.C.B. Karalliyadda is the Head of the Department of Agricultural Systems, Faculty of Agriculture, at Rajarata University of Sri Lanka. An expert in human ecology, environmental sociology, agricultural extension, and regional design, his work focuses on rural and community development. He is passionate about teaching, research, and outreach initiatives aimed at regional development and uplifting the living standards of rural communities. He holds a PhD from the United Graduate School of Agricultural Sciences, Kagoshima University, Japan; a Master of Regional Design in Arts and Economics from Saga University, Japan; a Master of Organizational Management; and a BSc in Agricultural Technology and Management from the University of Peradeniya, Sri Lanka.

Shashi S. Udumann

Shashi S. Udumann is an accomplished research professional currently serving as a Research Officer at the Coconut Research Institute of Sri Lanka. With a BSc in Export Agriculture and an MSc in Crop Science, she has expertise in experimental design, data analysis, and publishing research findings. Her work focuses on sustainable agriculture practices, soil amendments, and optimizing coconut cultivation. She has an impressive publication record, contributing to journals on topics like agroforestry, biochar applications, and waste management for agriculture.

Sudhanshu Singh

Sudhanshu Singh, as the Director of ISARC, spearheads the center's mandates and operations in South Asia to meet the evolving needs and expectations of farmers, consumers, stakeholders, and the wider scientific community in the rice sector, also working in Africa with the aim of South–South cooperation. With over 30 years of experience in agricultural sciences, notably in research, extension, and development; forging strategic alliances; and institutional management, he is a field agronomist with a substantial understanding of crop and natural resource management approaches for intensifying and diversifying rice-based production systems in South Asia. Dr. Singh's pioneering research on crop and natural resource management in fragile environments using stress-tolerant rice varieties and the introduction of scale-appropriate mechanization as an integrated approach in research and development initiatives has had a pronounced impact on rice-based systems in South Asia. He completed his PhD research at IRRI Philippine's headquarters on Submergence-tolerant (Sub1) rice and has an excellent publication history, with over 80 research papers in high-impact-factor journals, and has authored numerous books and chapters. Additionally, he holds credit as a co-developer for two patented machines to be used for precision DSR. During his academic and long professional journey, Dr. Singh has garnered many recognitions and awards, including the Gold Medal and Chancellor's Medal, during graduation and post-graduation, respectively, as well as the Eminent Scientist Award, the Lifetime Achievement Award, the CWSS Gold Medal, and recognition from the Indian Society of Agronomy, etc.

Sufiyan Bharucha

Sufiyan Bharucha is a Project Coordinator with the Department of Infrastructure in the Government of Northwest Territories. With a background in mechanical engineering and a Master of Engineering in Public Policy, he supports strategic infrastructure projects across the territory, drawing on experience in the automotive, renewable energy, and non-profit sectors.

Suryakanta Khandai

Suryakanta Khandai is working as a Senior Associate Scientist I: Mechanization and Postharvest at the International Rice Research Institute. Dr. Khandai has worked on research, development, and extension for farmers and other stakeholders, which included designing post-harvest farm equipment and assisting manufacturers by putting a focus on diversifying and intensifying rice-based production systems in South Asia. He received the Scientist of the Year (2022) Award for outstanding contributions in Farm Machinery & Power Engineering by the Astha Foundation at the 4th International Conference on ICAAAS-2022 and the Young Scientist Award for outstanding contributions in Agriculture Engineering by AEDS at the 5th International Conference on AAEBSD-2021. He received a gold medal in M.Tech (FMP) 2011-13. Dr. Khandai has published 32 research papers, 6 books/chapters, and 14 training modules, and has 2 patents to his name.

S. Vinujan

S. Vinujan is currently working as a Lecturer at the Department of Biosystems Technology, Faculty of Technology, University of Jaffna. He pursued an MSc degree in Environmental Forestry from the University of Peradeniya. He is an extremely conscientious, involved, and driven learner. He has published his scientific communications in various forums nationally and internationally. In addition to his passion for teaching, his research interests are expansive, including sustainable farming practices, crop production technologies, carbon mitigation, biodiversity conservation, crop interactions, remote sensing, and phytoremediation.

Swati Nayak

Swati Nayak is working as IRRI South Asia's Lead for Seed System and Product Management. Her work entails enhancing breeding impact by delivering genetic gain for farmer fields and positioning the right products in market segments. She also serves as the global nodal coordinator and lead for the 'Inclusive Delivery' Area of work for the Rice Seed System as part of the CGAIR Mega science programme,

'Breeding for Tomorrow'. Swati holds the prestigious title of Norman E. Borlaug Field Award Winner for 2023, received from the World Food Prize Foundation, endowed by the Rockefeller Foundation. Swati's experience spans 15 years of research and delivery expertise in rural innovation models, scaling and uptake of sustainable and climate-smart agriculture, noble germplasms, and quality seeds.

T.D. Nuwarapaksha

T.D. Nuwarapaksha is a distinguished agronomist at the Coconut Research Institute of Sri Lanka, dedicated to advancing sustainable agricultural practices in coconut cultivation. He holds a master's degree in Agri-Enterprise and Technology Management and a Bachelor of Science (Honors) in Agriculture from Wayamba University of Sri Lanka. His expertise lies in integrating innovative research, precision agriculture technologies, and carbon offset initiatives to promote environmentally responsible farming. Bridging scientific research with practical implementation, he develops climate-smart strategies that empower farmers and industries to adopt sustainable practices. His contributions extend beyond Sri Lanka, offering scalable solutions for global coconut-producing regions to balance productivity with environmental stewardship. By fostering collaboration among researchers, policymakers, and agricultural communities, he plays a pivotal role in shaping the future of sustainable coconut farming worldwide.

Trevon Tewari

Trevon Tewari is a data professional with an MSc in Data Science (Distinction) and a BSc in Chemical and Process Engineering from the University of the West Indies, St. Augustine. He has applied data-driven techniques across industries, including supply chain analytics, financial analysis, and process optimization. Skilled in Python, machine learning, and data visualization, Trevon specializes in developing automated solutions and extracting actionable insights from complex datasets. His academic work includes a published project on survey automation using advanced language models, demonstrating his ability to bridge research and real-world applications.

Umais Abdull Baqi

Umais Abdull Baqi serves as the Lead Field Engineer for the Pattullo Bridge Replacement Project, a major infrastructure initiative in British Columbia. In this capacity, Umais manages a team of engineers to deliver a comprehensive heavy civil project, overseeing the earthworks, substructures, utilities, and superstructure components. He holds a bachelor's degree in civil engineering and a master's in engineering and public policy, where his research focused on the intersection of climate change and its effects on smaller urban communities. Umais's academic work included developing climate resilience strategies, particularly for the Port Hope Climate Change Action Plan, and addressing urban flooding through policy development. These projects were completed in collaboration with the Municipality of Port Hope and Public Works Hamilton. Outside of his professional work, Umais is passionate about sports and intellectual pursuits. He enjoys boxing, golf, squash, and cricket, which help him stay active and engaged. He also has a deep interest in philosophy and history, exploring new ideas and gaining insights into the past that inform his approach to problem-solving in both his personal and professional life.

Virendar Kumar

Virendar Kumar is presently affiliated with IRRI South Asia Regional Centre, Varanasi, India. Dr. Kumar, holding a PhD in Agronomy, possesses more than 35 years of experience working in different capacities in all three streams of agriculture—research, teaching and extension—at CCS Haryana Agricultural University, in the capacity of Sr. Coordinator of KVKs, Principal, College of Agriculture, Consortium PI for the NAIP Project in Mewat district of Haryana, PI (Agronomy) for the AICRP on Arid Legumes, and associated scientist for the multi-institutional ACIAR Project on wheat quality, and has worked in RCTs on DSR, zero tillage, FIRBS, and farming system research in South Haryana[EE5.1]. Additionally, as an IRRI Consultant, he has 10 years of experience working on different projects: the BMGF-funded IRRAS Project in Bihar, India, for 3 years, and the World Bank-funded project APART in Assam for 6 ½ years. He is credited with 70 research papers, 10 book chapters, 6 review papers, 67 conference abstracts/extended summaries, 12 book/booklets, 42 popular articles, and several other forms of extension literature materials.

Wendy-Ann P. Isaac

Wendy-Ann P. Isaac is a Senior Lecturer in the Department of Food Production at the University of the West Indies, specializing in sustainable agriculture, weed science, and innovative farming technologies like protected and controlled environment agriculture. With over 22 years of teaching experience, she has guided both undergraduate and postgraduate students in areas such as crop production, pest management, and food security. She has authored and co-authored numerous books, book chapters, and research papers, focusing on sustainable food production, climate change impacts on agriculture, and food security in the Caribbean and beyond. Her work has been published in respected international journals, and she has co-edited key publications on topics like climate-smart agriculture and environmental sustainability. Beyond her academic contributions, Dr. Isaac is actively involved in research projects, community outreach, and training programmes aimed at improving agricultural practices and food security in the Caribbean. She also serves on the editorial boards of several leading journals, including *Agronomy, Frontiers in Sustainable Food Systems* and others.

Yagiz Ercin

Yagiz Ercin works as a Compliance Lead on the Hurontario LRT Transit project as part of the Design Build Joint Venture. With a background in engineering and policy, his role focuses on managing internal and external stakeholders, strategic decision-making, and effectively conveying project requirements to the project teams to ensure smooth execution. He holds a Master of Engineering and Public Policy from McMaster University, where he conducted several policy research projects, including scenario-based social impact assessments and long-term urban policy forecasting, with a focus on climate mitigation strategies. Before that, he earned a Master of Science in Structural Engineering from Boğaziçi University in Istanbul and a bachelor's degree in civil engineering from Yıldız Technical University, building a strong technical foundation. This unique combination of policy expertise and engineering knowledge has supported his ability to navigate complex infrastructure and regulatory challenges. A lifelong supporter of biking and an avid road cyclist himself, Yagiz enjoys cycling, whether for social events or commuting to work. He also enjoys reading about physics and history.

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