

Article

A Multidimensional Perspective for Women's Empowerment–Sustainability in Africa: Examining Multiple Sources of Heterogeneity and the Role of Renewable Energy

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Abstract

This study develops a novel composite index of women's empowerment for 54 African economies over the period 1996–2024 (unbalanced), addressing the limitations of existing fragmented measures. The index is constructed using principal component factor loadings and captures multiple dimensions of empowerment, including economic, socio-demographic, cultural, political, physical, and cognitive aspects, particularly for groups historically exposed to structural marginalization. We investigate the structural, distributional, and conditional effects of women's empowerment on environmental sustainability. Structural heterogeneity is addressed using heterogeneous panel estimators that allow coefficients to vary across countries. Distributional properties are examined through novel panel unit root tests that incorporate quantile-based approaches, enabling assessment of persistence and stationarity across different points of the conditional distribution rather than only the mean. Conditional effects are further explored by introducing renewable energy consumption as a moderating factor in the empowerment–environment nexus. The analysis is supported by a comprehensive set of second-generation econometric techniques that account for cross-sectional dependence and slope heterogeneity. In addition, panel causality tests incorporating Fourier smooth-transition specifications are employed to capture structural breaks and gradual regime shifts, ensuring that causal relationships are not assumed to be time-invariant but are allowed to evolve in response to structural change. The results reveal strong structural heterogeneity across African economies. While static estimators occasionally suggest a carbon-increasing effect of women's empowerment, heterogeneous and dynamic models consistently show that empowerment reduces carbon emissions in the long run. Renewable energy consumption independently exerts a significant mitigating effect on emissions across all specifications. However, the interaction between women's empowerment and renewable energy is positive and statistically significant, indicating that greater renewable energy adoption enhances the environmental effectiveness of women's empowerment, suggesting that gender-inclusive policies are more effective when accompanied by a cleaner energy transition. The study concludes that sustainable development in Africa requires integrated, context-specific policies that jointly promote women's empowerment, renewable energy expansion, and institutional strengthening.



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Keywords: environmental sustainability; women's empowerment; renewable energy; principal component analysis; panel; heterogeneity

1. Introduction

Human well-being increasingly depends on a development paradigm that simultaneously promotes economic progress, social inclusion, and environmental sustainability [1]. Within this framework, women's empowerment has emerged not only as a normative objective but also as a strategic lever for achieving sustainable development outcomes [2,3]. Enhancing women's access to education, healthcare, economic resources, and political participation is widely recognized as a fundamental driver of inclusive growth. However, beyond its intrinsic value, women's empowerment may also play a critical role in shaping environmental outcomes, particularly in resource-dependent economies.

Despite increasing recognition of the importance of women's empowerment for sustainable development, its environmental implications remain insufficiently understood, particularly in African economies. Women's empowerment extends beyond social equity by enhancing women's access to education, economic opportunities, political participation, and decision-making processes, all of which may influence environmental outcomes. Greater agency enables women to participate more actively in household and public decisions regarding energy use, resource management, and environmental governance, potentially encouraging more sustainable production and consumption patterns [4,5].

However, the relationship between women's empowerment and environmental sustainability is unlikely to be homogeneous across countries. Instead, it may vary systematically with underlying structural conditions. While the role of institutions has already been extensively examined in the literature as a key determinant of environmental outcomes, this study shifts the focus toward how structural differences across countries, particularly in energy systems and development pathways, shape the women's empowerment–CO₂ emissions nexus. In this context, renewable energy penetration is expected to play a key role by altering the carbon intensity of production and consumption, thereby shaping the environmental implications of women's empowerment.

Building on these insights, this study argues that the relationship between women's empowerment and CO₂ emissions exhibits both distributional and conditional heterogeneity. Specifically, the impact of women's empowerment is expected to differ across emission levels (low-, medium-, and high-emission regimes), reflecting differences in environmental pressure and development stages. At the same time, this relationship is likely to depend on the level of renewable energy adoption, which may weaken or strengthen the association between women's empowerment and CO₂ emissions by reshaping the energy mix and production technologies.

This study makes three key contributions to the existing literature on gender, energy, and environmental sustainability. First, unlike most previous studies that rely on narrow proxies of women's empowerment, such as female labor force participation, education, or political representation, this paper constructs a comprehensive multidimensional index of women's empowerment using principal component analysis. The index incorporates economic, socio-demographic, political, cultural, cognitive, and bodily dimensions, thereby providing a more holistic and internally consistent measure of empowerment.

Second, the study advances the empirical literature by jointly addressing three layers of heterogeneity that are typically treated in isolation in prior work: structural heterogeneity across countries, distributional heterogeneity across the CO₂ emissions distribution, and conditional heterogeneity through the interaction between women's empowerment and renewable energy consumption. In contrast to existing studies that primarily estimate average effects under homogeneous slope assumptions, this paper employs second-generation panel estimators that explicitly account for cross-sectional dependence, slope heterogeneity, and unobserved common factors, ensuring more reliable and context-specific estimates for African economies.

Third, the paper provides novel evidence on the state-dependent environmental effects of women's empowerment. While prior research generally assumes a uniform impact of empowerment on environmental outcomes, this study shows that the environmental benefits of women's empowerment are conditional on the level of renewable energy adoption and vary significantly across emission regimes. In particular, the results indicate that the negative effect of women's empowerment on CO₂ emissions weakens as renewable energy consumption increases, highlighting a nonlinear and context-dependent relationship that has been largely overlooked in the literature.

To the best of our knowledge, this is among the first studies to jointly integrate a multidimensional women's empowerment index, second-generation heterogeneous panel estimators, and a renewable energy interaction framework to examine environmental sustainability in African economies.

The remainder of the paper is organized as follows. Section 2 develops the theoretical framework and hypotheses. Section 3 presents the data and methodology. Section 4 discusses the empirical results. Section 5 concludes with policy implications.

2. Literature Review and Conceptual Framework

2.1. Measuring Women's Empowerment: Limitations and Advances

The empirical analysis of women's empowerment has been constrained by measurement challenges. Traditional indices, such as the Gender Empowerment Measure and the Gender-related Development Index, have been criticized for their narrow focus and limited ability to capture the multidimensional and context-specific nature of empowerment [6–10]. These measures often overlook intra-household dynamics, cultural norms, and qualitative dimensions such as agency and voice [11,12].

Similarly, sector-specific indicators—whether focused on economic participation, agriculture, or political representation—fail to provide a holistic perspective on empowerment [13–16]. Moreover, the arbitrary selection and weighting of indicators, along with limited statistical validation, have further constrained the robustness of existing measures [17–21].

In response, recent studies advocate for multidimensional approaches that capture the complex and dynamic nature of empowerment [11,22]. Building on this perspective, the present study constructs a composite index using principal component analysis (PCA), integrating socio-demographic, economic, political, cultural, educational, and physical dimensions (see Figure 1). These dimensions were selected based on [23] and other works. We detail them in Table A1 of Appendix A. This approach allows for a more comprehensive representation of women's empowerment and provides a robust basis for examining its role within broader development processes.

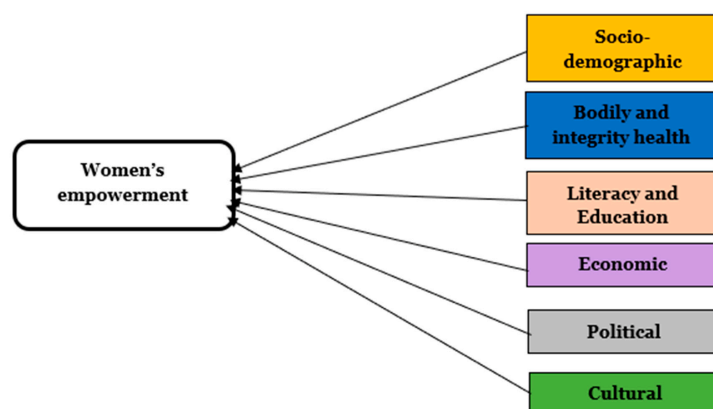


Figure 1. Dimensions of women's empowerment. See [23].

2.2. Theoretical Framework

This study argues that women's empowerment influences environmental sustainability through a unified causal mechanism linking women's agency, environmental decision-making, and carbon emissions. Women's empowerment expands women's access to education, economic opportunities, political participation, and decision-making authority, thereby strengthening their capacity to influence household, community, and national choices regarding resource use, energy consumption, environmental governance, and sustainable development. As women gain greater agency, they are better positioned to promote sustainable production and consumption practices, improve natural resource management, support cleaner energy transitions, and advocate for environmentally responsible policies. These behavioral and institutional changes ultimately contribute to lower CO₂ emissions [24–26]. See [27] for a succinct literature review. This mechanism is grounded in the Capability Approach and further reinforced by Feminist Political Ecology and Ecofeminism.

2.2.1. Women's Empowerment and Capability-Based Foundations of Environmental Sustainability

The Capability Approach provides the principal theoretical foundation for explaining how women's empowerment affects environmental sustainability. According to [28,29], development should be understood as the expansion of individuals' capabilities and freedoms to achieve valued outcomes. Women's empowerment, therefore, extends beyond increasing access to resources; it strengthens women's ability to exercise agency, participate in decision-making, and influence economic, social, and political processes.

This perspective is further developed by [30,31], who conceptualize empowerment as the interaction among resources, agency, and achievements. Resources include human, social, and economic capital embedded within institutional contexts [32,33], agency reflects the capacity for autonomous decision-making, and achievements represent realized development outcomes [28,34,35]. By expanding women's capabilities and agency, empowerment enables women to influence decisions related to resource allocation, energy use, environmental protection, and sustainable development.

Despite its theoretical importance, women's empowerment remains a multidimensional and dynamic concept that is difficult to measure [11,36,37]. Early studies conceptualize empowerment as a progressive process involving welfare, access, awareness, participation, and control [38,39]. Subsequent research defines empowerment as a multidimensional construct encompassing interpersonal, interactional, and behavioral components [40–44]. Regardless of the specific framework adopted, the common feature is that empowerment increases women's capacity to make decisions that influence development outcomes.

At the macro level, greater inclusion of women in political, economic, and civil institutions improves policy effectiveness by broadening representation, increasing accountability, and incorporating more diverse perspectives into public decision-making [45–48]. Consequently, women's empowerment strengthens governance processes that support environmentally sustainable development.

2.2.2. Women's Roles in Environmental Resource Use and Sustainability Outcomes

The environmental transmission mechanism linking women's empowerment to lower carbon emissions is explained by Feminist Political Ecology and Ecofeminism. Feminist Political Ecology emphasizes that environmental outcomes are shaped not only by individual agency but also by the socio-technical organization of resource systems, particularly energy infrastructures that structure access to and use of environmental resources [49]. From this

perspective, gendered inequalities in access to energy systems can constrain the extent to which women's empowerment translates into environmental improvements.

In many developing contexts, reliance on fossil-fuel-based and centralized energy systems limits households' ability to adopt clean and sustainable energy alternatives, even when women have greater decision-making power and environmental awareness. Thus, structural dependence on carbon-intensive energy can weaken the environmental effectiveness of empowerment.

The expansion of renewable energy reduces these structural constraints by decentralizing energy access and lowering barriers to clean energy adoption. This enables empowered women to more effectively translate their preferences into concrete environmental actions, such as adopting clean energy technologies and supporting low-carbon consumption.

While Feminist Political Ecology focuses on how gendered access to resources and energy systems shapes environmental outcomes, Ecofeminism extends this perspective by grounding these inequalities in broader patriarchal structures that jointly produce gender inequality and ecological degradation [50–54]. According to this perspective, the exploitation of nature and the marginalization of women are mutually reinforcing outcomes of hierarchical institutions that simultaneously encourage ecological degradation and social exclusion [55–57]. Strengthening women's political and economic participation, therefore, promotes both social inclusion and environmental stewardship by encouraging more equitable and sustainable management of environmental resources [58–62]. Ecofeminism further emphasizes that expanding women's agency contributes to sustainable development by challenging institutional arrangements that simultaneously reinforce environmental degradation and gender inequality [63–66].

Together, these perspectives suggest that women's empowerment reduces carbon emissions because greater agency improves environmental decision-making, strengthens environmental governance, and encourages more sustainable production and consumption practices.

H1. *Women's empowerment reduces environmental degradation in African countries.*

2.3. Conceptual Framework

The theoretical framework suggests that women's empowerment reduces CO₂ emissions by expanding women's capabilities and agency, thereby strengthening their participation in environmental decision-making and encouraging more sustainable production and consumption practices. However, the effectiveness of this mechanism is unlikely to be identical across African economies. Differences in socioeconomic conditions, emission profiles, and energy transitions may influence the extent to which women's agency translates into environmental improvements. Accordingly, this study examines three dimensions of heterogeneity: structural, distributional, and conditional.

2.3.1. Structural Heterogeneity of Women's Empowerment Effects

The Capability Approach and Feminist Political Ecology imply that the environmental benefits of women's empowerment depend on the context in which women's agency is exercised. Although empowerment expands women's ability to influence environmental outcomes, African countries differ substantially in their economic structures, governance arrangements, educational attainment, industrialization, and energy systems. These differences affect the opportunities available for women to participate in environmental decision-making and adopt sustainable practices.

Consequently, the same increase in women's empowerment may generate different environmental outcomes across countries because the underlying conditions that allow agency to influence production, consumption, and environmental governance vary consid-

erably. Rather than altering the theoretical mechanism itself, structural differences influence the magnitude of its environmental impact.

H2. *The environmental effect of women's empowerment differs across African countries.*

2.3.2. Distributional Heterogeneity of Women's Empowerment Effects

The theoretical mechanism may also operate differently depending on a country's position in the carbon emissions distribution. Countries with relatively low emissions generally face different environmental challenges than highly polluting economies. In lower-emission countries, women's empowerment may reduce emissions primarily through improved household behavior, community resource management, and environmental awareness. In contrast, in higher-emission economies, where industrial production and fossil fuel consumption are more important sources of emissions, greater women's participation in environmental governance, policy formulation, and sustainable economic decisions may produce larger environmental gains.

Thus, while the underlying mechanism—greater agency leading to improved environmental decision-making—remains unchanged, its effectiveness is expected to vary across different emission regimes.

H3. *The environmental effect of women's empowerment differs across low-, medium-, and high-emission regimes.*

2.3.3. Renewable Energy as a Conditional Mechanism

The theoretical framework further suggests that renewable energy strengthens the environmental benefits of women's empowerment by expanding the opportunities through which women's agency can influence environmental outcomes. Women's empowerment increases the willingness and capacity to support sustainable production and consumption, but renewable energy provides the technological means through which these preferences can generate measurable reductions in carbon emissions.

As renewable energy adoption increases, empowered women are better able to adopt clean household energy technologies, participate in renewable energy initiatives, support cleaner production processes, and influence policies that promote low-carbon development. Consequently, renewable energy complements the agency-enhancing effects of women's empowerment by facilitating the transition from environmentally responsible decisions to tangible reductions in fossil fuel dependence and CO₂ emissions.

Accordingly, the environmental effect of women's empowerment is expected to become stronger as renewable energy consumption increases.

H4. *Renewable energy strengthens the environmental benefits associated with women's empowerment by facilitating cleaner production and consumption patterns.*

3. Materials and Methods

3.1. Data

Data for this investigation are compiled from the World Development Indicators, World Governance Indicators, and Gender Statistics databases for 54 African countries (see Table 1). See <https://www.africa.com/54-african-countries/> for the complete list (accessed on 1 May 2025). The time coverage is 1996–2024 due to availability. We carefully selected the dimensions for our women's empowerment composite index, ensuring they are grounded in a robust theoretical framework (see Table A1 in the Appendix A for details). By thoroughly reviewing numerous academic sources, we have carefully selected

indicators that represent diverse aspects of empowerment, representing the inputs of PCA. Recognizing that PCA emphasizes variance maximization, we normalize the variables using four alternative processes: Z-transformation, Min-Max Normalization, Softmax Normalization, and Sigmoid Normalization. Each method has its specific features. The Z-score method deals with outliers. The Min-Max method transforms data with different scales so that they range between 0 and 1. The Softmax method combines the advantages of the z-score and min-max methods, ensuring that all values sum up to 1, and handles outliers without deleting observations from the set of variables. In contrast, the Sigmoid accommodates binary indicators. Both Softmax and Sigmoid techniques yield the same results. Given the missing observations, we have applied a linear interpolation of data to make use of the maximum amount of information in the indicators. The PCA results using Z-score or Min-Max in Table A2 indicate that the first three principal components have eigenvalues greater than one (11.36, 6.29, and 1.59), satisfying the Kaiser criterion for retention. Together, these three components explain 95.9% of the total variance, indicating that the selected empowerment indicators capture a common underlying multidimensional construct while retaining most of the information contained in the original variables. The same applies to Table A3 of the same Appendix A when using Softmax or Sigmoid. In the same tables, the loadings show how strongly each variable contributes to each principal component, with higher absolute values indicating stronger influence and the sign indicating direction of association. The first component generally captures a broad “overall empowerment/development” dimension (education, labor participation, institutions), while the second and third components reflect more specific contrasting sub-dimensions (e.g., health/fertility vs. labor-market structure or demographic structure). Following normalization, standard practices in PCA, including the Kaiser–Meyer–Olkin (KMO) test and Bartlett’s test of sphericity, are applied to assess the suitability of the data for PCA analysis. Table A4 in Appendix A reveals a highly significant Bartlett’s test and a KMO value exceeding 0.5 [67]. Another motivation for using PCA is the dimensionality reduction, which handles multiple indicators. Measurements of environmental sustainability and covariates are selected from well-documented references [68–70], etc.

Table 1. Summary of the variables.

Notation	Aspect	Definition
<i>Dependent variable</i>		
CO ₂ emissions	Environmental degradation	CO ₂ emissions (metric tons per capita)
<i>Controls</i>		
GDP per capita	Economic growth	GDP per capita, PPP (constant 2017 international \$)
Natural resource rents	Resource	Total natural resources rents (% of GDP)
Renewable energy consumption	Energy management	Renewable energy consumption (% of total final energy consumption)
Population size	Population size	Population, total
International tourism expenditures	Tourism	International tourism expenditures (current US\$)
Control of corruption	Governance	Measures how much people believe public power is used for private gain, including both small- and large-scale corruption.
Women’s empowerment index using Z-score	Women’s empowerment	A multidimensional composite index using PCA
Women’s Empowerment Index using Min-Max		
Women’s empowerment index using Softmax/Sigmoid		

Table 1. Cont.

Notation	Aspect	Definition
<i>Indicators for the composite index of women's empowerment</i>		
Age	Socio-demographic	Mean age at first marriage, female
Life expectancy		Life expectancy at birth, female (years)
Fertility		Fertility rate, total (births per woman)
Gender		Sex ratio at birth (male births per female births)
Fertility (adolescent)		Adolescent fertility rate (births per 1000 women ages 15–19)
Maternal	Bodily and integrity health	Maternal mortality ratio (modeled estimate per 100,000 live births)
HIV		Prevalence of HIV, female (% ages 15–24)
Abuse		The proportion of women subjected to physical and/or sexual violence in the last 12 months (% of ever-partnered women ages 15–49)
Violence		The proportion of women who have ever experienced any form of sexual violence (% of women ages 15–49)
Contraceptive		Contraceptive prevalence, any method (% of married women ages 15–49)
Contraceptive (modern)		Contraceptive prevalence, any modern method (% of married women ages 15–49)
Mutilation		Female genital mutilation prevalence (%)
Mortality		Mortality rate under 5 (per 1000 live births)
Literacy (youth)	Literacy and educational attainment	Literacy rate, female youth (% of females ages 15–24)
Literacy (adult)		Literacy rate, adult female (% of females ages 15 and above)
Secondary (gross)		School enrollment, secondary, female (% gross)
Secondary (net)		School enrollment, secondary, female (% net)
Tertiary (gross)		School enrollment, tertiary (% gross)
Unemployment	Economic participation and rights	Unemployment, female (% of female labor force) (modeled ILO estimate)
Wage		Wage and salaried workers, female (% of female employment) (modeled ILO estimate)
Self-employment		Self-employed, female (% of female employment) (modeled ILO estimate)
Labor		Labor force participation rate, female (% of female population ages 15+) (modeled ILO estimate)
Employment		Employment to population ratio, 15+, female (%) (modeled ILO estimate)
Professional		Female professional and technical workers (% of total)
Length		Length of paid maternity leave (calendar days)
Seats	Political participation and rights	The proportion of seats held by women in national parliaments (%)
Law		Women Business and the Law Index Score (scale 1–100)
Access	Cultural participation and rights	Used a mobile phone or the internet to access an account, female (% age 15+)
Buying		Used a mobile phone or the internet to buy something online, female (% age 15+)
Bills		Used a mobile phone or the internet to pay bills, female (% age 15+)
Money		Used a mobile phone or the internet to send money, female (% age 15+)
Parental leave		There is paid parental leave (1 = yes; 0 = no)
Art		Female share of graduates in Arts and Humanities programs (% , tertiary)

Note: Colors follow the dimensions of women's empowerment as shown in Figure 1.

According to Table 2, carbon dioxide emissions exhibit a negative mean and a slight right skew, while total greenhouse gas emissions demonstrate a positive mean and moderate left skew. Economic variables show relatively low dispersion, with GDP per capita

being moderately right-skewed and natural resource rents characterized by substantial left skew and leptokurtosis, indicating the presence of extreme values. Renewable energy consumption displays low variability and a slightly left-skewed distribution. Demographic and tourism-related variables, such as population size and international tourism expenditures, exhibit symmetric distributions with limited dispersion. Governance indicators generally exhibit positive skewness and moderate kurtosis, suggesting slight asymmetries in institutional quality. The composite measure of institutional quality is more distinctly right-skewed and leptokurtic, reflecting a concentration of lower values. Finally, the women's empowerment indices, regardless of the normalization method employed (Z-score, Min-Max, or Softmax/Sigmoid), exhibit similar central tendencies and variability, with slightly left-skewed, platykurtic distributions, indicating relatively flat shapes with fewer extreme values.

Table 2. Descriptive statistics.

Variables	N° Observations	Mean	S.D.	Min	Max	Skewness	Kurtosis
CO ₂ emissions	1293	−0.985	1.462	−6.943	2.337	0.328	2.497
GDP per capita	1306	8.102	0.941	6.219	10.483	0.467	2.397
Renewable energy consumption	1276	1.807	0.928	0.000	4.307	−0.333	2.237
Natural resource rents	1295	1.825	1.543	−6.749	4.218	−2.146	10.182
Population size	1404	15.834	1.573	11.244	19.179	−0.577	3.115
International tourism expenditures	957	20.200	2.212	12.612	25.328	−0.103	2.790
Control of corruption	1231	0.270	0.180	0.000	1.067	0.841	4.045
Women's empowerment index (Z-score)	988	1.357	0.660	0.000	2.512	−0.519	2.182
Women's empowerment index (Min-Max)	988	1.310	0.660	0.000	2.492	−0.423	2.077
Women Empowerment Index (Softmax/Sigmoid)	988	1.285	0.685	0.000	2.409	−0.451	1.961

According to Table 3, CO₂ emissions exhibit a strong positive correlation with GDP per capita ($r = 0.944$, $p < 0.01$), indicating that countries with higher income levels tend to record higher carbon emissions. Conversely, CO₂ emissions are negatively correlated with renewable energy consumption ($r = -0.323$, $p < 0.01$), natural resource rents ($r = -0.237$, $p < 0.01$), and population size ($r = -0.235$, $p < 0.01$), indicating inverse associations between these variables and carbon emissions. International tourism does not display a statistically significant correlation with CO₂ emissions.

Control of corruption is weakly and negatively correlated with CO₂ emissions ($r = -0.049$, $p < 0.10$) and population size ($r = -0.169$, $p < 0.01$), while exhibiting a small positive correlation with renewable energy use ($r = 0.068$, $p < 0.05$). The three alternative measures of women's empowerment (Z-score, Min-Max, and Softmax) are highly correlated with one another ($r = 0.989$ – 0.992 , $p < 0.01$), confirming that they capture a common underlying construct and demonstrating the consistency of the normalization approaches employed. Women's empowerment measures are not significantly correlated with CO₂

emissions, but they exhibit significant negative correlations with renewable energy consumption ($r = -0.320$ to -0.353 , $p < 0.01$) and positive correlations with population size ($r = 0.138$ to 0.161 , $p < 0.01$). The correlation matrix does not reveal serious multicollinearity concerns among the explanatory variables, apart from the expectedly high correlations among the alternative women's empowerment indices, which are therefore incorporated separately in the empirical models. The Variance inflation Variance (VIF) in Table A5 of Appendix A indicates a mean of 1.31. There is no concern of multicollinearity.

Table 3. Pairwise correlations.

Variables (in log)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(9)	(10)
(1) CO ₂ emissions	1.000								
(2) GDP per capita	0.944 ***	1.000							
(3) Renewable energy	−0.323 ***	−0.355 ***	1.000						
(4) Natural resource rents	−0.237 ***	−0.314 ***	0.051 *	1.000					
(5) Population size	−0.235 ***	−0.293 ***	−0.104 ***	0.349 ***	1.000				
(6) International tourism	0.005	0.018	0.019	0.002	−0.036	1.000			
(7) Control of corruption	−0.049 *	−0.002	0.068 **	−0.019	−0.169 ***	0.029	1.000		
(8) Women's empowerment using Z-score	−0.007	0.034	−0.352 ***	0.052	0.161 ***	−0.050	−0.019	1.000	
(9) Women's empowerment using Min-Max	−0.041	0.001	−0.320 ***	0.034	0.145 ***	−0.053	−0.018	0.992 ***	1.000
(10) Women's empowerment using Softmax	−0.007	0.030	−0.353 ***	0.055 *	0.138 ***	−0.052	−0.018	0.992 ***	0.989 ***

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3.2. Econometric Methodology

3.2.1. Econometric Framework

This study examines the relationship between women's empowerment, energy consumption, and CO₂ emissions in Africa, while explicitly accounting for structural and distributional heterogeneity and cross-sectional dependence. African economies are exposed to common shocks such as global energy price fluctuations, climate variability, and regional policy spillovers, which generate strong interdependencies across countries. Moreover, the environmental effects of women's empowerment are expected to vary across countries and emission regimes, and to depend on renewable energy consumption patterns.

The empirical specification is based on the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework of [71] and is given by:

$$I_{it} = aP_{it}^b A_{it}^c T_{it}^d$$

where I , P , A , and T stand for Impact, Population, Affluence, and Technology.

The logarithm transformation leads to

$$\text{LOGCO}_{2it} = \alpha_i + \theta \text{LOGWEI}_{it} + \mu (\text{LOGWEI}_{it} \times \text{LOGREN}_{it}) + \beta' \text{LOGX}_{it} + \varepsilon_{it} \quad (1)$$

where CO_{2it} denotes carbon dioxide emissions, WEI_{it} represents women's empowerment, REN_{it} denotes renewable energy consumption, and X_{it} is a vector of control variables. The interaction term captures conditional heterogeneity by allowing the effect of women's

empowerment to vary with renewable energy consumption. The STIRPAT framework is primarily designed to quantify how various socio-economic and demographic factors influence environmental outcomes. When the model is expressed in logarithmic form, the estimated parameters measure elasticity, indicating the proportional change in an environmental indicator associated with a 1% change in a given explanatory factor. These elasticity estimates provide information on the responsiveness of environmental outcomes to changes in the underlying determinants. Under a correctly specified and estimated model, the coefficients can be interpreted as the marginal contribution of each driving factor to environmental change.

The empirical analysis is organized in three stages. First, SCCE, CCEMG, DCCE, and CS-ARDL are employed to test the robustness of the long-run relationships under alternative estimators that account for cross-sectional dependence, heterogeneous slope coefficients, and dynamic adjustment, thereby assessing structural heterogeneity (H1 and H2). Second, MMQR and QCCEMG are estimated to examine whether these relationships vary across the conditional distribution of CO₂ emissions, providing evidence on distributional heterogeneity (H3). Finally, panel quantile causality analysis is conducted to investigate whether causal relationships differ across emission quantiles while accounting for heterogeneous dynamics and cross-sectional dependence through bootstrap inference." All estimators are repeated to account for the conditional hypothesis H4 (Women's empowerment-Renewable energy consumption -CO₂ emissions).

3.2.2. Static Common Correlated Effects (SCCE) Estimator

To address cross-sectional dependence arising from unobserved common factors, the study employs the Common Correlated Effects (CCE) estimator developed by [72]. This approach controls for latent common shocks by augmenting the regression model with cross-sectional averages of the dependent and explanatory variables, which serve as proxies for unobserved global and regional influences.

The model is specified as:

$$y_{it} = c_{iy} + b_{0i}x_{it} + d_{iz_{it}} + \varepsilon_{it} \quad (2)$$

This framework ensures consistent estimation in the presence of multifactor error structures and heterogeneous slope coefficients.

3.2.3. Mean Group (CCEMG) Estimator

To account for slope heterogeneity across countries, the MG estimator of [73] is employed. This estimator estimates country-specific regressions and computes the average of individual coefficients:

$$y_{it} = c_{iy} + \varphi_i y_{it-1} + b_{0i}x_{it} + \varepsilon_{yit} \quad (3)$$

The MG approach allows all parameters to vary across countries, capturing differences in structural characteristics, development levels, and environmental responses.

3.2.4. Dynamic Common Correlated Effects (DCCE) Estimator

To account for persistence in emissions and dynamic adjustment processes, the study employs the DCCE estimator of [74]. This estimator extends the CCE framework by incorporating lagged dependent variables and lagged cross-sectional averages:

$$y_{it} = c_{iy} + \varphi_i y_{it-1} + b_{0i}x_{it} + b_{1i}x_{it-1} + \sum_{l=0}^{pT} \delta'_{il} \bar{z}_{t-l} + \varepsilon_{yit} \quad (4)$$

For $i = 1, 2, \dots, N$, c_{iy} are the individual effects, $\bar{z}_t = \frac{1}{N} \sum_{i=1}^N z_{it}$, and pT is set to the integer part of $T^{\frac{1}{3}}$. The term ε_{yit} is the idiosyncratic error. This specification captures both

dynamic behavior and unobserved common shocks, while allowing slope heterogeneity across countries.

3.2.5. Cross-Sectionally Augmented ARDL (CS-ARDL)

To distinguish between short-run and long-run effects, the study employs the CS-ARDL approach of [75]. The model incorporates lagged variables and cross-sectional averages to control for common shocks:

$$y_{it} = c_{iy} + \sum_{j=1}^p \varphi_{ij} y_{it-j} + \sum_{j=0}^q b_{ij} x_{it-j} + \sum_{l=0}^{pT} \delta'_{il} \bar{z}_{t-l} + \varepsilon_{yit} \quad (5)$$

where p and q are the optimal lags for the dependent variable and the regressors, respectively. This framework allows for heterogeneous short-run dynamics and heterogeneous long-run relationships while remaining robust to cross-sectional dependence. The lag structure was restricted to one lag for the dependent variable. This specification follows the CS-ARDL literature, where a parsimonious lag structure is recommended for macro-panel data characterized by a relatively small time dimension and a moderate cross-sectional dimension. Using a single lag captures the main dynamic adjustment while avoiding over-parameterization and loss of degrees of freedom.

3.2.6. Method of Moments Quantile Regression (MMQR)

To capture distributional heterogeneity, the study employs the MMQR of [76]. This approach estimates the effect of regressors across different points of the conditional distribution of CO₂ emissions:

$$Q(\tau|X_{it}) = \alpha_{i(\tau)} + \beta_{i(\tau)} X_{it} + \varepsilon_{it} \quad (6)$$

where $Q(\tau|X_{it})$ denotes the τ^{th} conditional quantile of carbon emissions. $\alpha_{i(\tau)}$ captures country fixed effects, and $\beta_{i(\tau)}$ represents the vector of slope parameters that vary across quantiles.

Unlike mean-based estimators, MMQR allows the impact of women's empowerment and renewable energy consumption to differ across low-, medium-, and high-emission regimes.

3.2.7. Quantile Common Correlated Effects Mean Group (QCCEMG)

To jointly account for distributional heterogeneity, slope heterogeneity, and cross-sectional dependence, the study employs the QCCEMG estimator of [77]. The model is specified as:

This estimator allows quantile-specific responses while controlling for unobserved common factors through cross-sectional averages and their lags.

3.2.8. Causality Analysis

To complement the baseline estimations, the study applies the Toda–Yamamoto and quantile causality tests. The Fourier approach captures smooth structural breaks in the causal relationship, while quantile causality allows causal effects to differ across emission regimes. Together, these methods provide robust evidence on the direction and heterogeneity of causality between women's empowerment, renewable energy consumption, and CO₂ emissions.

4. Results and Discussion

4.1. Results

4.1.1. Preliminary Analysis

Assessing cross-sectional dependence and slope heterogeneity is essential for selecting the appropriate panel estimation framework. The presence of both cross-sectional dependence and heterogeneous slopes indicates that first-generation panel techniques are inappropriate, thereby supporting the use of second-generation approaches that account for cross-sectional interactions and country-specific heterogeneity.

The results in Panel A of Table 4 reveal strong evidence of cross-sectional dependence among the variables. The Pesaran's [78] statistics are significant for nearly all variables, while the Pesaran's [79] statistics further confirm dependence for CO₂ emissions, women's empowerment indicators, renewable energy, population, tourism expenditures, and control of corruption. These findings imply that shocks affecting one African economy can easily spread to others through trade integration, institutional linkages, regional cooperation, and common environmental and macroeconomic conditions.

Table 4. Cross-sectional dependence and Slope Homogeneity.

Panel A: Cross-Sectional Dependence	Overall	Overall	In Quantiles				
Variable	Pesaran's [78] Statistic	Pesaran's [79] Statistic	0.1	0.25	0.5	0.75	0.9
CO ₂ emissions (in log)	57.79 ***	−2.583 ***	−0.514	−1.861 *	−2.128 **	−1.524	−0.067
Women's empowerment using Z-score (in log)	115.64 ***	−2.348 **	4.432 ***	−0.649	−1.607	1.784 *	2.352 **
Women's empowerment using Min_Max (in log)	112.09 ***	−2.205 **	2.583 **	−0.695	−1.121	0.569	2.932 ***
Women's empowerment using Softmax (in log)	115.47 ***	−2.466 **	2.572 **	−1.399	−1.464	0.918	2.262 **
GDP per capita (in log)	70.58 ***	−0.726	3.422 ***	0.148	−0.670	0.872	1.749 *
Natural resource rents (in log)	26.12 ***	1.257	4.220 ***	3.068 ***	0.793	4.041 ***	4.968 ***
Renewable energy (in log)	32.10 ***	−1.932 *	3.915 ***	−1.188	−0.801	1.095	3.080 ***
Total population (in log)	79.58 ***	3.251 ***	4.131 ***	2.824 ***	2.453 **	0.980	−0.449
International tourism expenditures (in log)	7.57 ***	−2.748 ***	−1.954 *	−2.108 **	−1.895 *	−2.608 ***	−1.621
Control of corruption (in log)	1.21	−2.942 ***	−1.419	−1.276	−3.039 ***	−1.954 *	−2.262 **
Panel B: Slope homogeneity	Overall						
Method	Statistic						
Using Z-score-Delta	5.401 ***						
Using Z-score-Adj.	5.363 ***						
Using Min-Max-Delta	5.363 ***						
Using Min-Max-Adj.	9.893 ***						
Using Softmax/Sigmoid-Delta	5.302 ***						
Using Softmax/Sigmoid-Adj.	9.780 ***						

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

An additional contribution of this analysis is the use of quantile-based cross-sectional dependence testing, implemented via the 'xtpqroot' command in Stata version 15 [80]. This innovative approach enables evaluation of whether cross-sectional dependence varies across the conditional distribution of the variables, rather than relying solely on average effects. The results show that the intensity of dependence varies substantially across quantiles. CO₂ emissions exhibit stronger dependence around the middle quantiles, whereas women's empowerment indicators display significant dependence mainly at the lower and upper tails. Natural resource rents and population remain strongly dependent across several quantiles, reflecting common structural features among African economies. Renewable energy, tourism expenditures, and institutional quality also show significant dependence

at selected quantiles, highlighting heterogeneous spillover effects across countries and distributional regimes.

Panel B reports highly significant Delta and adjusted Delta statistics for all model specifications, leading to the rejection of the null hypothesis of slope homogeneity. This confirms that the relationship between women's empowerment and CO₂ emissions differs across African countries due to variations in governance quality, economic structures, demographic characteristics, and energy systems.

4.1.2. Stationarity Test Results

This study applies second-generation panel unit root techniques to investigate the stochastic properties of the variables while explicitly addressing cross-sectional dependence and heterogeneity in slope coefficients. Detailed results are presented in Table A6 of Appendix A, while the summary of the order of integration of each variable is summarized in Table 5. As shown in Table A6 (Panel A), we implement the cross-sectionally augmented IPS (CIPS) and cross-sectionally augmented Dickey–Fuller (CADF) tests under different deterministic settings, including intercept only and intercept with linear trend. In levels, the results provide mixed evidence regarding stationarity, as several variables fail to reject the unit root hypothesis under both specifications. However, after first differencing, all series become clearly stationary according to both CIPS and CADF statistics, indicating that the variables are integrated of order one, I(1).

Table 5. Conclusions of the Panel Unit Root Tests: Overall and per Quantile.

Variable	CIPS Conclusion	CADF Conclusion	Quantile Unit Root Conclusion	Integration Order
CO ₂ emissions	Stationary at the level	Stationary at the level	Stationary at most quantiles	I(0)
Women's empowerment (Z-score)	Stationary at the level	Stationary at the level	Stationary across quantiles	I(0)
Women's empowerment (Min–Max)	Stationary at the level	Stationary at the level	Stationary across quantiles	I(0)
Women's empowerment (Softmax/Sigmoid)	Stationary at the level	Stationary at the level	Stationary across quantiles	I(0)
GDP per capita	Non-stationary at the level	Non-stationary at the level	Non-stationary across quantiles	I(1)
Natural resource rents	Mixed evidence at the level	Stationary at the level (trend specification)	Mixed evidence across quantiles	I(1)
Renewable energy	Non-stationary at the level	Non-stationary at the level	Mixed evidence across quantiles	I(1)
Total population	Mixed evidence at the level	Stationary at the level	Stationary at central quantiles	I(1)
International tourism expenditures	Stationary at the level	Stationary at the level	Stationary at most quantiles	I(0)
Control of corruption	Non-stationary at the level	Non-stationary at the level	Non-stationary across quantiles	I(1)

To further enhance the analysis and capture distributional heterogeneity, we again employ the quantile-based panel unit root procedure using the 'xtpqroot' Stata version 15 command, which allows us to investigate unit root behavior across different points of the conditional distribution. This approach provides a useful extension to conventional mean-based tests by examining persistence not only on average but also across quantiles ranging from $\tau = 0.1$ to $\tau = 0.9$. In addition, we implement the quantile panel unit root test with common shocks developed by [81]. This framework extends Pesaran's [82] CIPS methodology to a quantile regression setting, allowing persistence to vary across the distribution. In contrast to the standard CIPS test, which focuses on average dynamics, the

CIPS(τ) statistics make it possible to identify whether persistence is stronger in the tails of the distribution than in its central part.

The results reported in Table A6 (Panel B) show that, in levels, most variables remain non-stationary across quantiles, although some cases display rejection of the unit root at specific quantiles, pointing to heterogeneous persistence depending on the position in the distribution. After first differencing, however, the quantile CIPS statistics consistently reject the null hypothesis across all quantiles and for all variables, confirming stationarity throughout the distribution. These results provide a solid basis for proceeding with panel cointegration methods that account for cross-sectional dependence and heterogeneity, such as the Westerlund's [83] error-correction-based framework, ensuring reliable inference in a non-stationary panel setting.

The Westerlund panel cointegration test in Table 6 provides evidence of a statistically significant long-run equilibrium relationship among the variables ($p < 0.05$). This finding suggests that the variables exhibit common long-term movements over time across African economies, indicating that shocks affecting one variable are associated with corresponding adjustments in the others in the long run.

Table 6. Westerlund cointegration test.

Test	Null Hypothesis (H0)	Alternative Hypothesis (H1)	Panels (N)	Avg. Periods (T)	Statistic
Variance ratio (using Z-Score)	No cointegration	Some panels are cointegrated	37	14.162	−2.2305 **
Variance ratio (using Min-Max)	No cointegration	Some panels are cointegrated	37	14.162	−2.2986 **
Variance ratio (using Softmax/Sigmoid)	No cointegration	Some panels are cointegrated	37	14.162	−2.1283 **

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.1.3. Empirical Results

To check for H1 and particularly H2, it is essential to proceed to a comparison between a series of estimators. Those include SCCE, CCEMG, DCCE, and CS-ARDL. The estimators show slight differences in the number of groups (countries) that arise because some methods require complete observations for lagged variables or interaction terms. Based on the outcomes presented in Table 7, it is evident that women's empowerment exhibits structurally heterogeneous effects on carbon emissions across African economies, depending on the estimator employed. The SCCE estimates show a positive and statistically significant relationship between women's empowerment and CO₂ emissions across all three empowerment measures. Given that SCCE is based on only two countries (34 observations), this result should be interpreted as a context-specific static association rather than a generalizable cross-country effect. Economically, it suggests that higher female participation in education, labor markets, and consumption is associated with greater energy demand and production activity, consistent with a scale effect of inclusion that increases emissions through higher economic activity. However, this estimate reflects limited cross-sectional variation and should not be interpreted as a continent-wide relationship. It captures a localized equilibrium association rather than a structural parameter for African economies.

In contrast, the CCEMG results indicate that greater women's empowerment is associated with lower carbon emissions across all specifications (supporting H1). A 1% increase in women's empowerment leads to approximately a 0.17% reduction in CO₂ emissions, suggesting economically meaningful environmental gains from expanding gender empowerment. This suggests that, after accounting for cross-country heterogeneity, strengthening women's empowerment contributes to long-run environmental sustainability in African

economies by reducing carbon emissions. These benefits are likely to arise through behavioral and institutional channels, including greater environmental awareness, more efficient household energy use, improved educational outcomes, and increased participation of women in governance and resource allocation decisions.

Table 7. Structural Heterogeneity: Short and Long-run Analyses.

Variables	SCCE			CCEMG			DCCE		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
LD Carbon emissions (log)				−0.842 *** (0.085)	−0.832 *** (0.084)	−0.863 *** (0.084)	−1.029 *** (0.053)	−1.025 *** (0.052)	−1.033 *** (0.052)
Women’s empowerment (log)	1.456 * (0.443)	1.167 * (0.339)	1.674 * (0.572)	−0.176 * (0.100)	−0.173 * (0.097)	−0.169 * (0.091)	−0.199 * (0.105)	−0.165 * (0.095)	−0.204 ** (0.101)
GDP per capita (log)	2.403 (2.241)	2.354 (2.215)	1.837 (2.319)	0.335 (0.234)	0.343 (0.216)	0.279 (0.222)	0.172 (0.217)	0.183 (0.239)	0.125 (0.228)
Renewable energy (log)	−0.070 (0.033)	−0.056 (0.031)	−0.063 (0.023)	−0.181 *** (0.035)	−0.173 *** (0.036)	−0.183 *** (0.036)	−0.186 *** (0.037)	−0.187 *** (0.039)	−0.180 *** (0.037)
Natural resource rents (log)	0.476 (0.238)	0.499 (0.217)	0.356 (0.271)	−0.031 (0.030)	−0.034 (0.031)	−0.036 (0.030)	−0.080 (0.052)	−0.074 (0.051)	−0.063 (0.051)
Total population (log)	−2.169 (1.741)	−1.949 (2.358)	−2.001 (1.152)	0.955 * (0.517)	0.971 * (0.508)	1.308 * (0.728)	3.170 (1.986)	3.469 * (1.930)	3.065 * (1.779)
Observations	34	34	34	503	503	503	734	734	734
Number of groups	2	2	2	37	37	37	37	37	37
Cross-sectional dependence in the residuals statistic	2.418	3.291	−1.373	0.114	−0.100	0.007	1.216	1.129	0.568
Cross-sectional dependence in the residuals <i>p</i> -value	0.016	0.001	0.170	0.909	0.920	0.994	0.224	0.259	0.570

Variables	CS-ARDL					
	Short-Run			Long-Run		
	(1)	(2)	(3)	(1)	(2)	(3)
LD Carbon emissions (log)	−0.039 (0.081)	−0.027 (0.078)	−0.023 (0.085)	−1.039 *** (0.081)	−1.027 *** (0.078)	−1.023 *** (0.085)
Women’s empowerment (log)	−0.058 (0.089)	−0.060 (0.091)	−0.096 (0.087)	−0.211 * (0.109)	−0.187 (0.121)	−0.155 * (0.091)
GDP per capita (log)	0.626 (0.393)	0.484 (0.374)	0.452 (0.388)	0.611 (0.481)	0.148 (0.437)	0.075 (0.476)
Renewable energy (log)	−0.149 *** (0.025)	−0.150 *** (0.027)	−0.145 *** (0.027)	−0.105 ** (0.046)	−0.108 ** (0.042)	−0.146 *** (0.038)
Natural resource rents (log)	0.019 (0.030)	0.026 (0.027)	0.047 (0.034)	0.076 (0.074)	0.044 (0.052)	−0.007 (0.045)
Total population (log)	2.994 (4.716)	3.634 (4.707)	3.671 (5.553)	1.566 (5.468)	3.773 (5.411)	4.581 (5.424)
LD GDP per capita (log)	−0.162 (0.251)	−0.154 (0.226)	−0.260 (0.247)			
L2D GDP per capita (log)	−0.035 (0.146)	−0.028 (0.156)	−0.040 (0.154)			
LD Renewable energy (log)	−0.018 (0.020)	−0.011 (0.020)	−0.015 (0.023)			
Observations	746	746	746	746	746	746
Number of groups	36	36	36	36	36	36
Cross-sectional dependence in the residuals statistic	0.691	0.267	0.226	0.691	0.267	0.226
Cross-sectional dependence in the residuals <i>p</i> -value	0.489	0.790	0.821	0.489	0.790	0.821

Note: SCCE: Static Common Correlated Effects, CCEMG: Common Correlated Effects with Mean Group, DCCE: Dynamic Common Correlated Effects, (1): Using Z-score, (2): Using Min-Max, (3): Using Softmax/Sigmoid. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is the first-differenced CO₂ emissions. Note: CS-ARDL: Cross-Sectionally Autoregressive Distributed Lag Model, (1): Using Z-score, (2): Using Min-Max, (3): Using Softmax/Sigmoid. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is the first-differenced CO₂ emissions. The CS-ARDL specification includes one lag of the dependent variable, a distributed lag structure of GDP (0–2 lags) and renewable energy (0–1 lag), while other regressors enter contemporaneously. Cross-sectional dependence is addressed using contemporaneous cross-sectional averages without additional lags.

The DCCE results further indicate that women’s empowerment contributes to lower carbon emissions (supporting H1). Economically, a 1% increase in women’s empowerment

is linked to a reduction in carbon emissions of up to 0.2%, suggesting that empowerment delivers modest but persistent environmental gains even in the presence of common continental and global shocks.

Similarly, the CS-ARDL framework highlights important dynamic heterogeneity between the short run and the long run. In the short run, the coefficients of women's empowerment are generally negative but statistically insignificant, indicating that African economies do not immediately translate empowerment gains into environmental improvements. This reflects structural rigidities, delayed institutional responses, and transitional adjustments in labor markets and consumption patterns. However, in the long run, the results become negative and, in several cases, statistically significant across specifications, confirming that sustained improvements in women's empowerment eventually contribute to lower carbon emissions. This long-run adjustment highlights that empowerment effects on the environment operate through cumulative structural transformation rather than immediate behavioral changes.

The error correction term in the CS-ARDL models is consistently negative and highly significant ($-1.03, p < 0.01$), indicating strong adjustment dynamics in carbon emissions across African economies. This suggests that deviations from equilibrium are corrected over time, although the speed of adjustment differs across countries. Such heterogeneity in adjustment behavior further confirms that African economies do not respond uniformly to shocks in emissions or empowerment, reinforcing the importance of using heterogeneous panel estimators.

A key feature of structural heterogeneity is also evident in the control variables. GDP per capita shows a generally positive but statistically insignificant relationship with carbon emissions across most estimators, suggesting that the income–emissions nexus is not uniform across African economies. This reflects divergent development trajectories, where some countries experience pollution-intensive industrial growth while others rely more on services or less carbon-intensive sectors. Consequently, economic growth does not exert a consistent environmental pressure across the panel.

Renewable energy consumption, however, consistently exerts a negative and statistically significant effect on emissions across the CCEMG, DCCE, and CS-ARDL frameworks. A 1% increase in renewable energy consumption is linked to a 0.18% reduction in CO₂ emissions, suggesting economic and environmental benefits from energy deployment. This indicates that despite structural differences across countries, renewable energy adoption uniformly contributes to environmental sustainability in Africa. This robustness suggests that energy transition policies are among the most homogeneous and effective environmental drivers across the continent.

The findings suggest that natural resource rents do not exert a uniform environmental effect across African economies. Economically, this implies that the impact of resource wealth depends on how resource revenues are managed. Where revenues reinforce extractive and fossil fuel-intensive activities, emissions are likely to increase, whereas investments in cleaner technologies, economic diversification, and institutional quality can mitigate environmental degradation.

Population effects exhibit structural heterogeneity, with coefficients varying in sign and statistical significance across estimators. Economically, this suggests that the environmental impact of population growth is not uniform but depends on country-specific conditions. Where it is significant, population growth is related to higher emissions through increased energy demand and urbanization pressures, whereas insignificant effects indicate that adequate infrastructure, energy systems, and environmental policies can offset demographic pressures.

To sum up, while the SCCE estimator yields a positive coefficient for women's empowerment, this estimate is based on a narrower sample, substantially reducing its representativeness relative to the remaining estimators. By contrast, the CCEMG, DCCE, and CS-ARDL estimators consistently indicate a negative long-run association using the full unbalanced panel. Accordingly, greater weight is placed on the broader body of evidence while acknowledging the SCCE result as a sensitivity finding rather than evidence against H1. Evidence also suggests that sustained women's empowerment, combined with renewable energy expansion, represents a key pathway toward long-term environmental sustainability in African economies. However, the magnitude and speed of these effects vary significantly across countries (supporting H2).

Additionally, the presence of a statistically significant and positive interaction effect (Women's empowerment $\times$ Renewable Energy) also points to important policy complementarities and constraints within African economies' transition pathways (see Table 8). The positive interaction coefficient indicates that renewable energy consumption moderates the emissions-reducing effect of women's empowerment. Although both women's empowerment and renewable energy independently reduce CO₂ emissions, the positive interaction implies that the marginal environmental benefit of women's empowerment becomes smaller as renewable energy consumption increases. Economically, this suggests diminishing marginal environmental returns between the two factors. As countries expand renewable energy deployment, a substantial share of emissions reductions is already achieved through cleaner energy production, leaving less scope for additional reductions attributable to improvements in women's empowerment. Similarly, empowered women may have already adopted cleaner technologies and environmentally sustainable behaviors in economies with greater renewable energy penetration, reducing the incremental impact of further empowerment on emissions. Moreover, the expansion of renewable energy infrastructure often requires large-scale investment, construction, and increased production activity during the transition phase, which may temporarily offset part of the environmental gains generated by women's empowerment. Therefore, while both policies remain individually effective in reducing emissions, their combined effect exhibits diminishing marginal environmental gains rather than a reinforcing relationship, leading to the rejection of H4. These findings suggest that promoting women's empowerment and renewable energy simultaneously remains essential for sustainable development, but policymakers should not expect their environmental benefits to increase proportionally when both are already well advanced.

Table 8. Structural and Conditional Heterogeneity: Short-run and long-run Analyses.

Variables	SCCE			CCEMG			DCCE		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
LD Carbon emissions (log)				−0.823 *** (0.041)	−0.820 *** (0.042)	−0.836 *** (0.040)	−0.949 *** (0.038)	−0.965 *** (0.042)	−0.977 *** (0.043)
LD Carbon emissions (log)				−0.823 *** (0.041)	−0.820 *** (0.042)	−0.836 *** (0.040)	−0.949 *** (0.038)	−0.965 *** (0.042)	−0.977 *** (0.043)
Women empowerment (log)	−0.890 ** (0.371)	−0.605 ** (0.280)	−0.497 * (0.259)	−0.465 ** (0.183)	−0.507 *** (0.190)	−0.430 ** (0.182)	−0.521 ** (0.221)	−0.496 ** (0.221)	−0.484 ** (0.212)
GDP per capita (log)	0.118 (0.421)	0.438 (0.339)	0.507 (0.379)	0.406 *** (0.127)	0.387 *** (0.129)	0.397 *** (0.125)	0.529 ** (0.249)	0.491 * (0.258)	0.320 (0.225)
Renewable energy (log)	−0.582 *** (0.194)	−0.547 ** (0.218)	−0.462 ** (0.205)	−0.504 *** (0.128)	−0.527 *** (0.130)	−0.475 *** (0.118)	−0.543 *** (0.177)	−0.546 *** (0.171)	−0.521 *** (0.160)
Natural resource rents (log)	−0.017 (0.058)	0.069 * (0.039)	0.056 (0.040)	−0.011 (0.018)	−0.014 (0.018)	−0.011 (0.017)	0.027 (0.023)	0.020 (0.024)	0.040 * (0.024)
Total population (log)	−2.783 (1.924)	−2.109 * (1.232)	−2.024 * (1.128)	0.617 ** (0.302)	0.643 ** (0.281)	0.708 * (0.363)	0.245 (1.463)	0.530 (1.045)	0.910 (1.319)

Table 8. Cont.

Variables	SCCE			CCEMG			DCCE		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Women empowerment × Renewable energy (LR)	0.241 ** (0.110)	0.236 ** (0.116)	0.181 * (0.110)	0.153 ** (0.069)	0.171 ** (0.070)	0.143 ** (0.064)	0.156 * (0.092)	0.170 ** (0.085)	0.144 * (0.086)
Observations	734	837	837	734	734	734	837	837	837
Number of groups	37	37	37	37	37	37	37	37	37
Cross-sectional dependence in the residuals statistic	0.088	−2.489	−2.343	0.699	0.515	0.920	−0.852	−0.923	−0.974
Cross-sectional dependence in the residuals <i>p</i> -value	0.930	0.013	0.019	0.485	0.606	0.358	0.394	0.356	0.330

Variables	CS-ARDL					
	Short-run			Long-run		
	(1)	(2)	(3)	(1)	(2)	(3)
LD Carbon emissions (log)	−0.103 (0.087)	−0.054 (0.060)	−0.097 (0.076)	−1.103 *** (0.087)	−1.054 *** (0.060)	−1.097 *** (0.076)
Women empowerment (log)	−0.829 *** (0.291)	−0.979 *** (0.295)	−0.779 *** (0.270)	−1.012 ** (0.420)	−1.203 *** (0.339)	−0.951 *** (0.348)
GDP per capita (log)	0.212 (0.375)	0.670 ** (0.322)	0.007 (0.348)	0.574 (0.745)	0.257 (0.488)	0.161 (0.749)
Renewable energy (log)	−0.724 *** (0.250)	−0.782 *** (0.211)	−0.691 *** (0.200)	−0.837 *** (0.279)	−0.975 *** (0.280)	−0.793 *** (0.230)
Natural resource rents (log)	0.006 (0.023)	0.089 * (0.048)	0.027 (0.028)	0.033 (0.033)	0.083 ** (0.039)	0.056 (0.038)
Total population (log)	12.795 (8.065)	6.800 (6.342)	7.556 (5.235)	9.989 (8.589)	6.689 (6.941)	8.516 (6.590)
Women empowerment × Renewable energy (LR)				0.329 ** (0.149)	0.412 *** (0.139)	0.315 ** (0.124)
LD Carbon emissions (log)	−0.103 (0.087)	−0.054 (0.060)	−0.097 (0.076)			
LD GDP per capita (log)	0.353 (0.262)	−0.066 (0.186)	0.280 (0.254)			
L2D GDP per capita (log)	0.183 (0.254)		0.178 (0.222)			
LD Renewable energy	−0.047 (0.030)	−0.009 (0.020)	−0.041 (0.030)			
D Women empowerment (log)	−0.829 *** (0.291)	−0.979 *** (0.295)	−0.779 *** (0.270)			
D Women empowerment × Renewable energy (log)	0.279 ** (0.139)	0.319 *** (0.114)	0.256 ** (0.107)			
Observations	693	780	693	693	780	693
Number of groups	33	36	33	33	36	33
Cross-sectional dependence in the residuals statistic				−0.665	−2.138	−1.208
Cross-sectional dependence in the residuals <i>p</i> -value				0.506	0.033	0.227

Note: SCCE: Static Common Correlated Effects, CCEMG: Common Correlated Effects with Mean Group, DCCE: Dynamic Common Correlated Effects, (1): Using Z-score, (2): Using Min-Max, (3): Using Softmax/Sigmoid. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is the first-differenced CO₂ emissions. Note: CS-ARDL: Cross-Sectionally Autoregressive Distributed Lag Model, (1): Using Z-score, (2): Using Min-Max, (3): Using Softmax/Sigmoid. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is the first-differenced CO₂ emissions. The CS-ARDL specification includes one lag of the dependent variable, a distributed lag structure of GDP (0–2 lags) and renewable energy (0–1 lag), while other regressors enter contemporaneously. Cross-sectional dependence is addressed using contemporaneous cross-sectional averages without additional lags. For specification (2), a distributed lag structure of GDP (0–1 lags) is considered.

Figure 2 shows the long-run marginal effect of women's empowerment on CO₂ emissions across different levels of renewable energy adoption. We take the results of DCCE and the Z-score method for illustrative purposes. At low levels of renewable energy, the marginal effect is negative, indicating that empowerment reduces emissions. As renewable energy increases, this effect becomes less negative and eventually turns positive, suggesting that the environmental benefits of empowerment diminish and may even reverse at higher

levels of renewable energy penetration. The confidence interval is wide at low renewable energy levels but narrows somewhat in the middle range, and the significance of the effect is weak where the confidence band crosses zero.

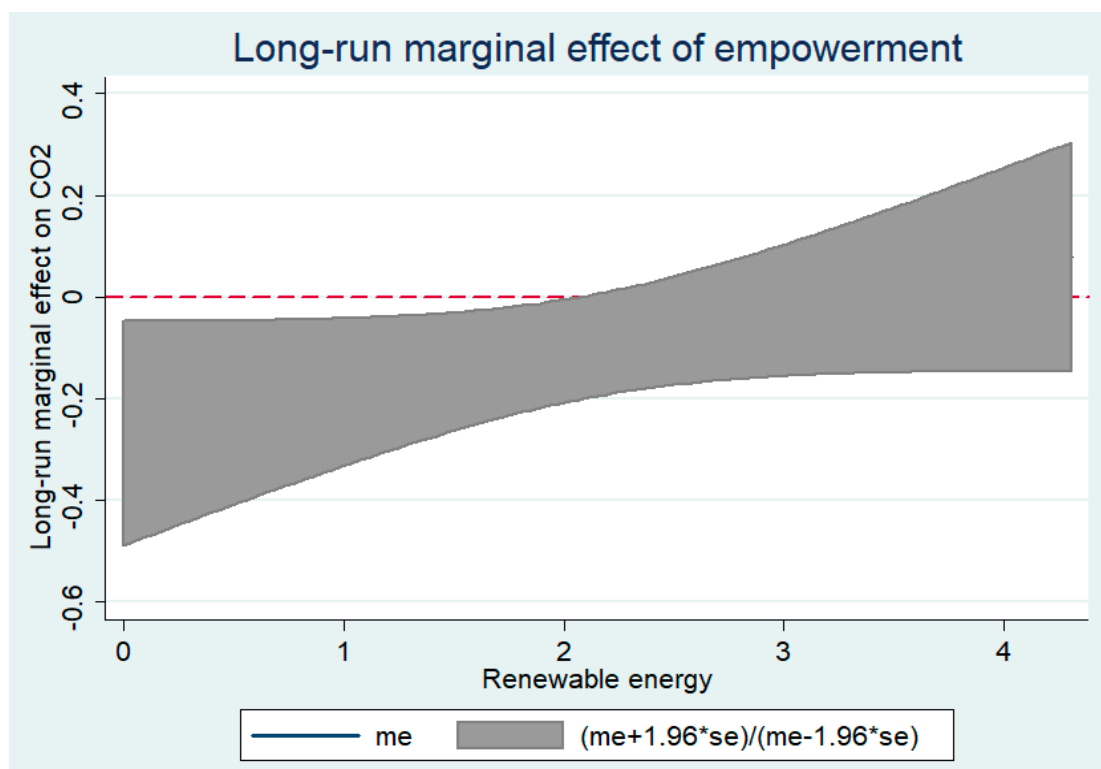


Figure 2. Long-run marginal (me) effect at 95% of Women’s empowerment using Z-score and DCCE. Source: Stata version 15.

The distributional heterogeneity results reported in Panels A–C of Table 9 reveal that the effects of the explanatory variables on carbon emissions vary across different points of the conditional emissions distribution, thereby confirming the presence of heterogeneous environmental dynamics across African economies. Most notably, women’s empowerment is associated with lower carbon emissions across most of the conditional distribution, although the strength of this relationship varies across quantiles. Economically, this suggests that the environmental gains from empowerment are not uniform but tend to persist across different emissions regimes, becoming more stable in higher-emission countries. However, the magnitude of this mitigating effect differs along the distribution. In Panels A and C, the negative impact is stronger at the lower quantiles (Q10) and gradually weakens toward the upper quantiles (Q90), indicating that women’s empowerment is relatively more effective in reducing emissions in lower-emitting economies than in highly polluting countries. Conversely, the Min–Max specification in Panel B shows a slight strengthening of the negative effect toward higher quantiles, although the differences remain modest. GDP per capita is positively associated with emissions across all quantiles, with a slightly stronger effect at higher emission levels, suggesting that the environmental cost of economic growth intensifies in more carbon-intensive economies. In contrast, renewable energy consistently reduces emissions throughout the distribution, highlighting its role as a robust mitigation channel regardless of emission intensity. Population growth also increases emissions across all quantiles, although the declining magnitude at higher quantiles indicates that demographic pressures are more binding in relatively lower-emission contexts. Natural resource rents display heterogeneous effects, shifting from mitigating emissions at lower quantiles to amplifying them at upper quantiles, implying that resource dependence becomes environ-

mentally more harmful as economies move toward higher emission regimes. Governance quality, proxied by control of corruption, generally reduces emissions, though its mitigating effect weakens at higher quantiles, suggesting diminishing institutional effectiveness in more pollution-intensive settings. By contrast, international tourism expenditures show no systematic impact on emissions, indicating a limited direct environmental role within the sample.

Table 9. Distributional Heterogeneity.

Panel A: Women's Empowerment Using Z-Score							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
Women's empowerment (log)	−0.143 *** (0.038)	0.010 (0.019)	−0.159 *** (0.045)	−0.152 *** (0.039)	−0.143 *** (0.038)	−0.134 *** (0.045)	−0.127 ** (0.053)
GDP per capita (log)	0.690 *** (0.074)	0.014 (0.041)	0.668 *** (0.116)	0.678 *** (0.094)	0.690 *** (0.074)	0.703 *** (0.071)	0.712 *** (0.080)
Natural resource rents (log)	−0.000 (0.018)	0.029 *** (0.009)	−0.047 ** (0.023)	−0.026 (0.020)	0.000 (0.018)	0.027 (0.020)	0.046 ** (0.023)
Renewable energy (log)	−0.110 *** (0.016)	0.004 (0.008)	−0.116 *** (0.025)	−0.113 *** (0.020)	−0.110 *** (0.016)	−0.107 *** (0.014)	−0.104 *** (0.015)
Total population (log)	0.909 *** (0.136)	−0.058 (0.061)	1.003 *** (0.153)	0.960 *** (0.136)	0.908 *** (0.136)	0.854 *** (0.157)	0.816 *** (0.182)
International tourism expenditures (log)	−0.004 (0.003)	−0.000 (0.001)	−0.004 (0.004)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)
Control of corruption (log)	−0.193 *** (0.053)	0.024 (0.026)	−0.232 *** (0.066)	−0.214 *** (0.056)	−0.192 *** (0.053)	−0.170 *** (0.060)	−0.154 ** (0.070)
Constant	−20.705 *** (2.286)	0.848 (1.085)	−22.082 *** (2.564)	−21.460 *** (2.268)	−20.688 *** (2.291)	−19.902 *** (2.712)	−19.336 *** (3.186)
Panel B: Women's Empowerment Using Min-Max							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
Women's empowerment (log)	−0.115 *** (0.035)	−0.006 (0.018)	−0.105 *** (0.040)	−0.110 *** (0.035)	−0.115 *** (0.035)	−0.120 *** (0.042)	−0.124 ** (0.050)
GDP per capita (log)	0.684 *** (0.075)	0.014 (0.041)	0.661 *** (0.118)	0.671 *** (0.095)	0.685 *** (0.075)	0.698 *** (0.070)	0.708 *** (0.079)
Natural resource rents (log)	−0.001 (0.018)	0.029 *** (0.009)	−0.048 ** (0.024)	−0.026 (0.020)	0.000 (0.018)	0.026 (0.019)	0.046 ** (0.022)
Renewable energy (log)	−0.110 *** (0.016)	0.003 (0.008)	−0.116 *** (0.025)	−0.113 *** (0.021)	−0.110 *** (0.016)	−0.107 *** (0.014)	−0.105 *** (0.015)
Total population (log)	0.910 *** (0.135)	−0.058 (0.059)	1.004 *** (0.156)	0.961 *** (0.138)	0.908 *** (0.135)	0.856 *** (0.153)	0.815 *** (0.177)
International tourism expenditures (log)	−0.004 (0.003)	−0.000 (0.002)	−0.003 (0.004)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)
Control of corruption (log)	−0.193 *** (0.053)	0.020 (0.026)	−0.226 *** (0.067)	−0.211 *** (0.057)	−0.192 *** (0.053)	−0.174 *** (0.059)	−0.159 ** (0.069)
Constant	−20.729 *** (2.282)	0.868 (1.055)	−22.132 *** (2.615)	−21.488 *** (2.307)	−20.694 *** (2.290)	−19.908 *** (2.643)	−19.298 *** (3.109)
Panel C: Women's Empowerment Using Softmax/Sigmoid							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
Women's empowerment (log)	−0.127 *** (0.035)	0.011 (0.017)	−0.145 *** (0.041)	−0.137 *** (0.035)	−0.127 *** (0.035)	−0.117 *** (0.041)	−0.110 ** (0.048)
GDP per capita (log)	0.688 *** (0.075)	0.012 (0.040)	0.669 *** (0.115)	0.678 *** (0.092)	0.688 *** (0.075)	0.700 *** (0.072)	0.707 *** (0.081)
Natural resource rents (log)	0.000 (0.018)	0.029 *** (0.009)	−0.047 ** (0.023)	−0.025 (0.020)	−0.000 (0.019)	0.028 (0.021)	0.046 * (0.024)
Renewable energy (log)	−0.110 *** (0.016)	0.003 (0.008)	−0.116 *** (0.024)	−0.113 *** (0.020)	−0.110 *** (0.016)	−0.107 *** (0.014)	−0.105 *** (0.015)
Total population (log)	0.912 *** (0.136)	−0.056 (0.062)	1.006 *** (0.151)	0.962 *** (0.134)	0.913 *** (0.136)	0.858 *** (0.160)	0.822 *** (0.186)

Table 9. Cont.

Panel C: Women's Empowerment Using Softmax/Sigmoid							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
International tourism expenditures (log)	−0.004 (0.003)	−0.000 (0.001)	−0.004 (0.004)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.004)
Control of corruption (log)	−0.196 *** (0.053)	0.026 (0.027)	−0.238 *** (0.065)	−0.218 *** (0.056)	−0.196 *** (0.053)	−0.171 *** (0.061)	−0.155 ** (0.071)
Constant	−20.776 *** (2.292)	0.843 (1.098)	−22.174 *** (2.525)	−21.519 *** (2.232)	−20.785 *** (2.290)	−19.968 *** (2.770)	−19.424 *** (3.253)
Observations	524	524	524	524	524	524	524
Number of groups	37	37	37	37	37	37	37

Note: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is CO₂ emissions.

The interaction between women's empowerment and renewable energy is positive and becomes significant mainly in the upper quantiles (Q75–Q90) of Table 10. Economically, this suggests that in high-emission economies, the environmental benefits of women's empowerment are partially offset in the presence of renewable energy expansion, reflecting transitional dynamics during structural energy transformation. This implies that while both factors independently contribute to emissions reduction, their joint effect is not fully additive in more carbon-intensive contexts, possibly due to adjustment costs or shifts in energy use patterns during the transition to cleaner energy systems. Overall, the results highlight that the empowerment–energy–emissions nexus is conditional on the stage of environmental and structural development.

Table 10. Distributional and Conditional Heterogeneity.

Panel A: Women's Empowerment Using Z-Score							
Variable	Location	Scale	Q10	Q25	Q50	Q75	Q90
Women's empowerment (log)	−0.248 *** (0.070)	−0.007 (0.038)	−0.237 ** (0.117)	−0.243 *** (0.091)	−0.249 *** (0.069)	−0.255 *** (0.061)	−0.259 *** (0.066)
GDP per capita (log)	0.691 *** (0.074)	0.007 (0.042)	0.679 *** (0.121)	0.685 *** (0.094)	0.691 *** (0.073)	0.698 *** (0.069)	0.702 *** (0.077)
Natural resource rents (log)	0.002 (0.018)	0.027 *** (0.009)	−0.044 * (0.023)	−0.021 (0.019)	0.003 (0.018)	0.027 (0.020)	0.044 * (0.023)
Renewable energy (log)	−0.171 *** (0.046)	−0.008 (0.027)	−0.158 * (0.085)	−0.164 ** (0.065)	−0.172 *** (0.045)	−0.179 *** (0.033)	−0.184 *** (0.033)
Total population (log)	0.920 *** (0.136)	−0.059 (0.063)	1.020 *** (0.159)	0.971 *** (0.138)	0.917 *** (0.136)	0.865 *** (0.157)	0.828 *** (0.181)
Tourism expenditures (log)	−0.004 (0.003)	0.000 (0.001)	−0.004 (0.004)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)
Control of corruption (log)	−0.203 *** (0.053)	0.023 (0.027)	−0.241 *** (0.071)	−0.222 *** (0.059)	−0.201 *** (0.053)	−0.181 *** (0.059)	−0.167 ** (0.068)
Women's empowerment × Renewable energy	0.040 * (0.024)	0.007 (0.013)	0.029 (0.042)	0.034 (0.032)	0.040 * (0.024)	0.046 ** (0.019)	0.050 ** (0.020)
Constant	−20.719 *** (2.280)	0.949 (1.108)	−22.333 *** (2.652)	−21.537 *** (2.279)	−20.669 *** (2.293)	−19.823 *** (2.698)	−19.235 *** (3.145)
Observations	524	524	524	524	524	524	524
Panel B: Women's Empowerment Using Min-Max							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
Women's empowerment (log)	−0.211 *** (0.069)	−0.029 (0.038)	−0.164 (0.114)	−0.187 ** (0.090)	−0.214 *** (0.067)	−0.239 *** (0.059)	−0.258 *** (0.064)
GDP per capita (log)	0.686 *** (0.075)	0.008 (0.042)	0.674 *** (0.120)	0.680 *** (0.095)	0.687 *** (0.073)	0.693 *** (0.069)	0.698 *** (0.078)

Table 10. Cont.

Panel B: Women's Empowerment Using Min-Max							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
Natural resource rents (log)	0.000 (0.018)	0.027 *** (0.008)	−0.045 * (0.023)	−0.023 (0.020)	0.002 (0.018)	0.026 (0.019)	0.044 ** (0.022)
Renewable energy (log)	−0.169 *** (0.048)	−0.012 (0.027)	−0.149 * (0.087)	−0.159 ** (0.067)	−0.170 *** (0.046)	−0.181 *** (0.033)	−0.189 *** (0.033)
Total population (log)	0.927 *** (0.136)	−0.060 (0.061)	1.027 *** (0.159)	0.979 *** (0.139)	0.922 *** (0.137)	0.869 *** (0.155)	0.830 *** (0.179)
International tourism expenditures (log)	−0.004 (0.003)	−0.000 (0.001)	−0.004 (0.004)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)
Control of corruption (log)	−0.205 *** (0.054)	0.018 (0.028)	−0.235 *** (0.073)	−0.220 *** (0.060)	−0.203 *** (0.054)	−0.187 *** (0.059)	−0.175 ** (0.068)
Women's empowerment × Renewable energy (log)	0.039 (0.025)	0.010 (0.014)	0.023 (0.044)	0.031 (0.034)	0.040 (0.024)	0.049 ** (0.019)	0.055 *** (0.020)
Constant	−20.851 *** (2.285)	1.001 (1.081)	−22.511 *** (2.635)	−21.710 *** (2.294)	−20.769 *** (2.303)	−19.896 *** (2.678)	−19.237 *** (3.128)
Observations	524	524	524	524	524	524	524
Panel C: Women's Empowerment Using Softmax/Sigmoid							
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
Women's empowerment (log)	−0.221 *** (0.060)	−0.006 (0.032)	−0.210 ** (0.097)	−0.215 *** (0.077)	−0.221 *** (0.060)	−0.227 *** (0.054)	−0.231 *** (0.059)
GDP per capita (log)	0.690 *** (0.074)	0.006 (0.041)	0.679 *** (0.120)	0.684 *** (0.094)	0.690 *** (0.073)	0.696 *** (0.069)	0.700 *** (0.078)
Natural resource rents (log)	0.002 (0.018)	0.027 *** (0.009)	−0.044 * (0.023)	−0.021 (0.019)	0.003 (0.018)	0.028 (0.020)	0.044 * (0.023)
Renewable energy (log)	−0.166 *** (0.041)	−0.008 (0.023)	−0.153 ** (0.073)	−0.159 *** (0.056)	−0.166 *** (0.040)	−0.173 *** (0.031)	−0.178 *** (0.031)
Total population (log)	0.921 *** (0.136)	−0.059 (0.063)	1.023 *** (0.157)	0.974 *** (0.137)	0.919 *** (0.137)	0.866 *** (0.158)	0.829 *** (0.183)
International tourism expenditures (log)	−0.004 (0.003)	0.000 (0.001)	−0.004 (0.004)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)	−0.004 (0.003)
Control of corruption (log)	−0.204 *** (0.053)	0.023 (0.027)	−0.243 *** (0.070)	−0.224 *** (0.058)	−0.203 *** (0.053)	−0.183 *** (0.059)	−0.169 ** (0.069)
Women's empowerment × Renewable energy (log)	0.037 * (0.021)	0.007 (0.011)	0.025 (0.036)	0.031 (0.028)	0.038 * (0.021)	0.044 ** (0.018)	0.048 *** (0.019)
Constant	−20.783 *** (2.289)	0.963 (1.112)	−22.423 *** (2.622)	−21.627 *** (2.267)	−20.747 *** (2.299)	−19.881 *** (2.725)	−19.282 *** (3.180)
Observations	524	524	524	524	524	524	524

Note: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is CO₂ emissions.

4.2. Robustness Checks

To address the potential endogeneity, we estimate the CCEMG model using an instrumental variable approach. The second and third lags of natural resource rents are used as instruments because natural resource dependence is highly persistent over time owing to fixed resource endowments, extraction infrastructure, and long-term production decisions. Therefore, past resource rents are strongly correlated with current resource rents. Potential endogeneity is most likely to arise for natural resource rents because resource exploitation and environmental outcomes may be jointly determined. Accordingly, natural resource rents are instrumented using their second and third lags. By contrast, women's empowerment and renewable energy consumption are treated as exogenous because they primarily reflect slow-moving structural and policy-related processes whose evolution is not expected to respond contemporaneously to changes in CO₂ emissions. Furthermore,

the CCEMG framework accounts for unobserved common factors through cross-sectional averages and controls for dynamics via the lagged dependent variable, thereby mitigating residual endogeneity arising from omitted common shocks. Since the interaction term is constructed as the product of two exogenous regressors, it is likewise treated as exogenous. Moreover, after controlling for contemporaneous covariates and unobserved common factors, earlier resource rents are not expected to affect current CO₂ emissions directly, satisfying the exclusion restriction. It should be noted that the ‘xtcce’ command of Stata version 15 used for the estimator does not provide conventional post-estimation diagnostic tests for instrument validity, such as weak instrument or overidentification tests. The results are readable in Table A7 and confirm the previous observations (H1 marginally accepted and H4 rejected).

Then, the QCCEMG results, used as a robustness check for the MMQR estimates, confirm the main findings while explicitly accounting for cross-sectional dependence, slope heterogeneity, and unobserved common factors (Table A8 of Appendix A). We have used the recent command ‘xtcspqardl’ available in the R version 4.4.1 packages.

The key relationships between women’s empowerment, renewable energy, and carbon emissions remain stable, indicating that the baseline results are not driven by omitted global shocks or model specification bias. The estimates also highlight significant heterogeneity across African countries, showing that the magnitude of effects varies depending on country-specific structural characteristics, energy systems, and exposure to common shocks such as global energy price fluctuations and climate-related disturbances. This confirms that the empowerment–environment and energy–environment relationships are not uniform across the continent.

In addition, the results are consistent with the distributional heterogeneity observed in the MMQR framework, reinforcing that the impact of key variables differs across low-, medium-, and high-emission regimes.

The quantile results in Table A9 confirm strong distributional heterogeneity in the empowerment–energy–environment nexus across African economies. Renewable energy consistently exerts a robust negative effect on carbon emissions in both the short and long run across all quantiles, underscoring its central role in decarbonization.

Women’s empowerment shows heterogeneous effects: it is generally emissions-reducing in the short run, particularly at higher emission quantiles, but displays mixed long-run effects depending on the distribution and specification, reflecting context-specific structural conditions.

The interaction between women’s empowerment and renewable energy introduces important conditional dynamics. While its short-run effect is limited and becomes more relevant at higher quantiles, the long-run interaction is often positive, especially in high-emission regimes. This suggests that the joint expansion of both factors is not purely additive, but reflects transitional structural adjustments where overlapping channels may dampen immediate environmental gains.

Adjustment coefficients indicate stable and relatively fast convergence toward the long-run equilibrium across all quantiles.

To ascertain the direction of causality between women’s empowerment and carbon emissions, it is necessary to complement the regression analysis with causality tests, since statistically significant coefficients do not automatically imply causal relationships. Accordingly, this study employs the newly developed Stata version 15 command ‘xtpcaus’, which performs panel quantile causality analysis while accounting for heterogeneous dynamics across the conditional distribution of the dependent variable. Importantly, the bootstrap *p*-values generated by this procedure account for cross-sectional dependence

among panel units, thereby ensuring more reliable inference in the presence of interconnected African economies.

The findings reported in Table A10 reveal a strong and consistent unidirectional causal relationship running from women's empowerment to CO₂ emissions across all quantiles and across the three alternative measures of women's empowerment (Z-score, Min–Max, and Softmax/Sigmoid). Specifically, the Wald statistics are positive and highly significant at the 1% level throughout the entire distribution, indicating that women's empowerment Granger-causes carbon emissions in both low- and high-emission economies. The causal effect appears strongest around the median and upper quantiles, as reflected in the larger Wald statistics at Q50 and Q75, suggesting that the influence of women's empowerment on environmental outcomes becomes more pronounced in economies with moderate to high levels of pollution. The Sup-Wald statistic, defined as the supremum of the quantile-specific Wald statistics, indicates whether causality exists at any point in the conditional distribution. The highly significant Sup-Wald values confirm that the causal effect of women's empowerment on CO₂ emissions is present at least at one quantile and, given the consistently significant Wald statistics across all quantiles, is pervasive throughout the entire distribution.

Conversely, there is no evidence of causality from CO₂ emissions to women's empowerment. The Wald statistics are small and statistically insignificant across all quantiles and empowerment measures. These findings therefore support the presence of a unidirectional causal nexus from women's empowerment to environmental quality rather than a feedback relationship.

A second round of robustness checks accounts for structural breaks by employing the Fourier Toda–Yamamoto causality approach available in the 'xtpcaus' framework, which is robust to both smooth structural shifts and cross-sectional dependence (see Table A11 for the unit root test). The results in Table A12 reveal a robust and asymmetric relationship between women's empowerment and environmental degradation. Across all empowerment indicators, we find strong evidence that empowerment Granger-causes CO₂ emissions in a nonlinear and structurally evolving manner, while no reverse causality is detected. These findings suggest that empowerment operates as a structural determinant of emissions dynamics rather than being endogenously shaped by environmental conditions. The heterogeneity across empowerment measures further indicates that the environmental impact of empowerment depends on the specific dimension captured, with the Min-Max method exhibiting the most stable causal effects.

4.3. Discussion

Our findings are generally inconsistent with a growing body of literature that identifies a positive and uniform relationship between women's empowerment and environmental quality in other regions [84–90]. These studies typically assume or document a stable and homogeneous effect of women's empowerment on environmental outcomes across countries [91]; in India and Sweden, as well as [92–94]. In contrast, our results provide evidence of pronounced structural and distributional heterogeneity in the African context, where the effect of women's empowerment on environmental quality is not uniform and varies across countries, estimators, and distributional regimes.

In examining macroeconomic factors, we find that economic growth tends to exacerbate the distributional environmental degradation, corroborating the results of [68,95,96], yet contrasting the findings of [70,97,98]. We note, however, that the mentioned studies have considered a uniform effect. The observed pattern suggests that the region is likely still on the upward-sloping segment of the Environmental Kuznets Curve (EKC), as theorized by [99]. This implies that environmental quality may eventually improve once income lev-

els reach a certain threshold, as higher economic capacity facilitates investment in cleaner technologies and stricter environmental regulations. In this context, governance emerges as a critical policy lever that can mitigate the adverse environmental effects of economic expansion. Stronger anti-corruption mechanisms enhance the effectiveness of environmental governance by limiting regulatory evasion, reducing rent-seeking activities, and improving the implementation of environmental policies [100]. Improved anti-corruption measures may also facilitate the allocation of public resources to renewable energy investments, cleaner technologies, and sustainable infrastructure, thereby reinforcing long-term environmental sustainability. The stronger effects observed at some quantiles further suggest that institutional improvements may be particularly effective in countries experiencing relatively higher environmental pressure or weaker governance systems, where corruption more severely undermines environmental regulation and policy enforcement [101]. Some views advance that the sustainability of renewable energy depends not only on increasing renewable capacity but also on efficiently coordinating generation, storage, loads, and grid operations under uncertainty. It shows that advanced optimization of integrated energy systems can improve renewable energy utilization, reduce operating costs, and enhance system reliability, thereby supporting a more resilient and economically sustainable low-carbon energy transition (see [102]). Beyond its direct effect, renewable energy also plays an important moderating role in the women's empowerment–environmental sustainability nexus [103]. The positive interaction with women's empowerment implies that the joint increase in women's empowerment and renewable energy consumption is associated with a greater marginal impact on carbon emissions than either effect alone would suggest. In other words, while both women's empowerment and renewable energy independently reduce emissions, their combined effect indicates a complex structural adjustment process in African economies. This may reflect overlapping transmission channels, where both variables influence emissions through similar demand-side mechanisms such as consumption patterns, urbanization, and energy use intensity, thereby generating diminishing marginal environmental returns when both factors expand simultaneously. From a structural perspective, this result suggests that the environmental benefits of renewable energy may partially offset or reshape the way empowerment affects emissions, particularly in economies undergoing rapid socio-economic transformation. In early stages of development, empowerment-driven increases in economic participation may still rely on energy-intensive systems, while renewable energy expansion may not yet be sufficiently deep to fully decouple growth from emissions. Consequently, the positive interaction captures transitional dynamics rather than a purely adverse effect.

Furthermore, our estimations reveal an ambiguous relationship between natural resource rents and environmental outcomes. Specifically, natural resource benefits do not appear to influence per capita CO₂ emissions [104]. On the one hand, such revenues may finance sustainable development initiatives; on the other hand, they risk promoting overexploitation, pollution, and biodiversity loss if governance is weak. Moreover, an overreliance on resource rents can contribute to economic and political volatility, with deleterious consequences for long-term environmental stewardship [16].

The impact of tourism expenditures on environmental sustainability is less substantial than that reported by [70], indicating possible contextual differences in the environmental footprint of the tourism sector or the effectiveness of environmental regulations. Ultimately, our findings indicate that population growth substantially increases resource demand, thereby intensifying industrial activity and pollution.

5. Conclusions

5.1. Summary of Findings

This study provides a multidimensional and integrated assessment of the relationships between women's empowerment, renewable energy, and environmental sustainability in African countries.

The findings reveal that the relationship between women's empowerment, renewable energy, and environmental quality in African countries is structurally heterogeneous, distributionally uneven, and conditionally dependent on economic and institutional contexts. Women's empowerment is generally associated with lower carbon emissions, but its magnitude varies across countries and emission regimes, indicating strong distributional heterogeneity. Renewable energy consistently reduces emissions, yet its interaction with women's empowerment suggests that environmental gains are not purely additive and depend on transitional structural dynamics within economies.

These results highlight that the empowerment–environment nexus is not uniform but shaped by country-specific development pathways, energy structures, and governance conditions. Consequently, environmental and gender-related outcomes cannot be generalized across Africa, as policy effectiveness differs depending on structural characteristics and the level of emissions intensity. This underscores the importance of accounting for heterogeneity when designing policies that link gender equality, energy transition, and environmental sustainability in African economies.

5.2. Policy Recommendations

Based on these findings, several policy implications emerge. First, policies promoting women's empowerment should be designed with explicit attention to country heterogeneity, as the results show that their environmental benefits vary across emission regimes. In high-emission countries, empowerment policies are likely to yield stronger environmental returns and should therefore be prioritized alongside aggressive mitigation strategies.

Second, renewable energy expansion should remain a central policy priority, given its consistently negative effect on emissions across all specifications. However, since its interaction with women's empowerment is non-additive, renewable energy policies should be coordinated with gender policies rather than implemented in isolation, particularly during transitional phases of energy restructuring.

Third, in countries located at different points along the emission distribution, differentiated policy design is required. Low- and middle-emission countries may benefit more from strengthening foundational drivers such as education, labor market inclusion, and institutional quality, while high-emission economies require integrated policy packages that jointly accelerate clean energy deployment and structural transformation of gender roles.

Fourth, the observed weakening of effects at higher emission levels for some variables implies diminishing marginal effectiveness of isolated policy interventions. This calls for policy bundling, where gender equality measures, renewable energy investment, and governance reforms are implemented simultaneously to avoid saturation effects and enhance environmental returns.

Fifth, since the empowerment–environment relationship is contingent on structural characteristics, governments should incorporate country-specific diagnostics into climate policy design, using emission intensity and energy structure as criteria to tailor interventions rather than adopting uniform regional strategies.

The heterogeneous nature of the empirical findings further suggests that policy design should be differentiated according to countries' environmental profiles. For relatively low-emission economies, policy priorities should focus on strengthening the foundational determinants of women's empowerment, including education, healthcare, financial in-

clusion, and participation in local environmental governance. These investments can help prevent future carbon-intensive development pathways while promoting inclusive growth. In contrast, higher-emission African economies should complement empowerment policies with accelerated renewable energy deployment, cleaner industrial technologies, and stronger environmental regulations, where the environmental gains associated with women's empowerment appear to be more pronounced.

5.3. Limitations and Avenues for Future Research

We acknowledge some limitations of our study. First, although the multidimensional women's empowerment index is theoretically grounded and statistically validated using principal component analysis (PCA), the resulting index remains sensitive to the selection of its constituent indicators. Alternative indicators or weighting schemes may produce somewhat different dimensions of empowerment, reflecting the inherent complexity of measuring such a multidimensional concept. Second, the unbalanced nature of the panel, together with data interpolation for some missing observations, may introduce measurement uncertainty despite allowing broader country coverage. Third, although the econometric framework explicitly accounts for cross-sectional dependence, slope heterogeneity, structural breaks, and long-run dynamics, it cannot fully capture the effects of sudden climate shocks, extreme weather events, or natural disasters that may temporarily influence carbon emissions independently of the structural relationships examined in this study. Finally, caution should be exercised when generalizing the findings to all African countries. The continent exhibits substantial heterogeneity in economic development, institutional quality, energy systems, and environmental conditions, and our own empirical results demonstrate that the effects of women's empowerment vary considerably across countries and across different emission regimes. Future research could therefore examine more homogeneous regional groupings, explicitly incorporate climate-related shocks, or explore alternative multidimensional empowerment measures using micro-level or country-specific data. One could also further explore the sectoral dimensions of resource governance, the role of technological innovation, and the integration of qualitative indicators of empowerment [105,106]. Such extensions would provide deeper insights into the mechanisms through which gender inclusion shapes sustainability outcomes in developing economies.

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Abbreviations

The following abbreviations are used in this manuscript:

CADF	Cross-sectionally Augmented Dickey–Fuller
CCEMG	Common Correlated Effects with Mean Group
CIPS	Cross-sectionally Im-Pesaran-Shin
CS-ARDL	Cross-Sectionally Autoregressive Distributed Lag
CSA	Cross-Sectionally Average
DCCE	Dynamic Common Correlated Effects
EKC	Environmental Kuznets Curve
MMQR	Method Of Moments Quantile Regression
QCCEMG	Quantile Common Correlated Effects Mean Group

SCCE	Static Common Correlated Effects
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology
VIF	Variance Inflation Factor

Appendix A

First, this appendix details the procedure for selecting the final indicators of women's empowerment, as illustrated in Figure 1. It then presents the results of the PCA used to construct the composite empowerment indices. Second, we provide the detailed results of panel unit root tests: overall and per quantile. Finally, we provide a robustness check of the results while accounting for endogenous covariates. Then, we test for distributional (and distributional and conditional) heterogeneity through QCCEMG, before exposing the results of panel causalities (without and with structural breaks).

Table A1. Theoretical grounding of the women's empowerment indicators.

Notation	Aspect	Definition	Source	Argument
Age	Socio-demographic	Mean age at first marriage, female	Gender Statistics	Early marriage is often associated with limited access to education, health services, and autonomy. Raising the age at first marriage enhances agency and life choices [29].
Life expectancy	Socio-demographic	Life expectancy at birth, female (years)	Gender Statistics	Higher life expectancy reflects better access to healthcare and social well-being, signaling improved female status in society [28].
Fertility	Socio-demographic	Fertility rate, total (births per woman)	Gender Statistics	Lower fertility is linked to greater access to reproductive health services, education, and economic opportunities for women [30,107].
Gender	Socio-demographic	Sex ratio at birth (male births per female births)	Gender Statistics	Disproportionate sex ratios often reflect gender discrimination and undervaluation of female lives [108].
Fertility (adolescent)	Socio-demographic	Adolescent fertility rate (births per 1000 women ages 15–19)	Gender Statistics	High adolescent fertility is associated with lower educational attainment and limited socio-economic mobility [109].
Maternal	Bodily and integrity health	Maternal mortality ratio (modeled estimate, per 100,000 live births)	Gender Statistics	High maternal mortality signals poor healthcare access and gender inequality in health systems [110].
HIV	Bodily and integrity health	Prevalence of HIV, female (% ages 15–24)	Gender Statistics	Gender norms and lack of empowerment increase women's vulnerability to HIV, especially among young women [111].
Abuse	Bodily and integrity health	Proportion of women subjected to physical and/or sexual violence in the last 12 months (% of ever-partnered women ages 15–49)	Gender Statistics	Violence against women undermines autonomy and physical integrity, affecting participation in social and economic life [112].
Violence	Bodily and integrity health	Proportion of women who have ever experienced any form of sexual violence (% of women ages 15–49)	Gender Statistics	A key indicator of bodily autonomy and structural gender inequality [113].
Contraceptive	Bodily and integrity health	Contraceptive prevalence, any method (% of married women ages 15–49)	Gender Statistics	Access to contraception enhances women's reproductive autonomy and life planning [114].
Contraceptive (modern)	Bodily and integrity health	Contraceptive prevalence, any modern method (% of married women ages 15–49)	Gender Statistics	Modern methods provide more effective control over reproduction, contributing to empowerment [115].
Mutilation	Bodily and integrity health	Female genital mutilation prevalence (%)	Gender Statistics	A violation of bodily integrity and rights rooted in patriarchal cultural norms [116].

Table A1. Cont.

Notation	Aspect	Definition	Source	Argument
Mortality	Bodily and integrity health	Mortality rate, under-5 (per 1000 live births)	Gender Statistics	Reflects maternal education, health access, and care practices, indirectly linked to women's status [117].
Literacy (youth)	Literacy and education attainment	Literacy rate, youth female (% of females ages 15–24)	Gender Statistics	Literacy is a foundational capability that enhances access to resources and decision-making [29].
Literacy (adult)	Literacy and education attainment	Literacy rate, adult female (% of females ages 15 and above)	Gender Statistics	Empowered women are more likely to engage in community, political, and economic life [28,118].
Secondary (gross)	Literacy and education attainment	School enrollment, secondary, female (% gross)	Gender Statistics	Gross enrollment captures broad access and demand for female education [119].
Secondary (net)	Literacy and education attainment	School enrollment, secondary, female (% net)	Gender Statistics	Net enrollment indicates completion and appropriate age progression in education [120].
Tertiary (gross)	Literacy and education attainment	School enrollment, tertiary (% gross)	Gender Statistics	Tertiary education enhances leadership capacity, earnings, and autonomy [121].
Unemployment	Economic participation and rights	Unemployment, female (% of female labor force) (modeled ILO estimate)	Gender Statistics	Unemployment reflects structural inequalities and access barriers to labor markets [122].
Wage	Economic participation and rights	Wage and salaried workers, female (% of female employment) (modeled ILO estimate)	Gender Statistics	Formal wage employment enhances social security and independence [123,124].
Self-employment	Economic participation and rights	Self-employed, female (% of female employment) (modeled ILO estimate)	Gender Statistics	Self-employment may indicate necessity or entrepreneurship depending on context [125].
Labor	Economic participation and rights	Labor force participation rate, female (% of female population ages 15+) (modeled ILO estimate)	Gender Statistics	Indicates economic independence and access to opportunities [126].
Employment	Economic participation and rights	Employment to population ratio, 15+, female (%) (modeled ILO estimate)	Gender Statistics	Higher ratios suggest broader engagement in economic activities [23].
Professional	Economic participation and rights	Female professional and technical workers (% of total)	Gender Statistics	Access to high-skilled jobs reflects empowerment in professional spheres [127].
Length	Economic participation and rights	Length of paid maternity leave (calendar days)	Gender Statistics	Supports women's work–life balance and job retention [128].
Seats	Political participation and rights	Proportion of seats held by women in national parliaments (%)	Gender Statistics	Political participation is a key dimension of agency and influence [129].
Law	Political participation and rights	Women Business and the Law Index Score (scale 1–100)	Gender Statistics	Captures legal rights and institutional environments affecting empowerment [130].
Access	Cultural participation and rights	Used a mobile phone or the internet to access an account, female (% age 15+)	Gender Statistics	Digital inclusion boosts financial autonomy and social engagement [131].
Buying	Cultural participation and rights	Used a mobile phone or the internet to buy something online, female (% age 15+)	Gender Statistics	Reflects digital literacy and economic participation [132].
Bills	Cultural participation and rights	Used a mobile phone or the internet to pay bills, female (% age 15+)	Gender Statistics	Regular digital financial activity indicates autonomy in household management [132].
Money	Cultural participation and rights	Used a mobile phone or the internet to send money, female (% age 15+)	Gender Statistics	Ability to send money denotes financial agency and support networks [132].

Table A1. Cont.

Notation	Aspect	Definition	Source	Argument
Parental leave	Cultural participation and rights	There is paid parental leave (1 = yes; 0 = no)	Gender Statistics	Gender-equitable leave fosters shared caregiving and supports work-family balance [133].
Art	Cultural participation and rights	Female share of graduates in Arts and Humanities programmes (%; tertiary)	Gender Statistics	Represents cultural participation and symbolic empowerment [29].

Note: The colors follow the dimensions of women's empowerment in Figure 1.

Table A2. PCA eigenvalues and variance explained using the Z-score or Min-Max method.

	Eigenvalue	Difference	Proportion	Cumulative
Comp1	11.36047	5.072181	0.540974647784872	0.540974647784872
Comp2	6.288289	4.697218	0.299442270165274	0.840416917950146
Comp3	1.591071	0.6909295	0.0757652697314217	0.916182187681567
Comp4	0.9001415	0.6207142	0.0428638719101451	0.959046059591713
Comp5	0.2794273	0.1030733	0.0133060590978171	0.97235211868953
Comp6	0.176354	0.0437172	0.00839780775227199	0.980749926441801
Comp7	0.1326368	0.0287311	0.0063160367628551	0.987065963204657
Comp8	0.1039057	0.0441776	0.00494788943242142	0.992013852637078
Comp9	0.0597281	0.0136735	0.00284419463810561	0.994858047275184
Comp10	0.0460546	0.0214368	0.00219307572784164	0.997051123003025
Comp11	0.0246178	0.0077982	0.00117227594318179	0.998223398946207
Comp12	0.0168196	0.0058452	0.000800933164374576	0.999024332110582
Comp13	0.0109744	0.0065176	0.000522590365948794	0.99954692247653
Comp14	0.0044568	0.001269	0.000212228526658459	0.999759151003189
Comp15	0.0031878	0.001843	0.000151799967977435	0.999910950971166
Comp16	0.0013448	0.0008985	0.0000640380817291094	0.999974989052895
Comp17	0.0004463	0.000375	0.0000212523764691415	0.999996241429364
Comp18	0.0000713	0.00006393	$3.39523737900469 \times 10^{-6}$	0.999999636666744
Comp19	0.00000737	0.00000711	$3.50952306918156 \times 10^{-7}$	0.99999998761905
Comp20	0.00000026	0.00000026	$1.23809497691616 \times 10^{-8}$	1
Comp21	0	-21.00000443	0	1
Factor Loadings				
Variable	Comp1	Comp2	Comp3	
zee/min-max_age	0.10672239	-0.30427058	0.32056208	
zee/min-max_life	0.27870923	-0.00198096	-0.24636364	
zee/min-max_fertility	-0.15298591	0.00623643	-0.61749466	
zee/min-max_gender	-0.06525197	-0.35933616	0.20367327	
zee/min-max_adol	-0.09148008	0.33449272	-0.08449835	
zee/min-max_maternal	-0.18330718	0.21268474	0.42398254	
zee/min-max_contraceptive	0.24425319	0.20185185	0.10791211	
zee/min-max_contraceptivemodern	0.22156108	0.24851452	0.06272205	
zee/min-max_mortality	-0.28592141	-0.03198475	0.06565624	
zee/min-max_literacy_h	-0.21960327	-0.25911880	-0.03607537	
zee/min-max_literacy_t	0.26067489	0.18709817	0.01866036	
zee/min-max_secondary_s	0.29131311	0.01569931	-0.06791057	
zee/min-max_secondary_t	0.29052502	-0.01746515	-0.11301705	
zee/min-max_tertiary	0.22976712	-0.22308433	0.17322421	
zee/min-max_unemp	0.27690430	-0.02712609	0.12311241	
zee/min-max_wage	-0.13804182	0.30589510	-0.03235319	
zee/min-max_selfemp	0.13798582	-0.30586836	0.03257940	
zee/min-max_labor	-0.07453877	0.31063770	0.34079320	
zee/min-max_emp	-0.27083992	0.12084319	-0.00309981	
zee/min-max_seats	0.27062255	0.02123181	-0.13023938	
zee/min-max_law	0.21364072	0.25637502	0.08691245	

Table A3. PCA eigenvalues and variance explained using the Softmax or Sigmoid method.

	Eigenvalue	Difference	Proportion	Cumulative
Comp1	11.37413	5.035044	0.541625208486393	0.541625208486393
Comp2	6.339086	4.781204	0.301861221593491	0.843486430079885
Comp3	1.557882	0.6617206	0.0741848530874185	0.917671283167303
Comp4	0.8961614	0.6167922	0.0426743500480879	0.960345633215391

Table A3. Cont.

Comp5	0.2793692	0.1272464	0.0133032945108485	0.973648927726239
Comp6	0.1521228	0.0253909	0.00724394246114067	0.98089287018738
Comp7	0.1267319	0.0389119	0.00603485205104714	0.986927722238427
Comp8	0.08782	0.0123731	0.00418190453329398	0.991109626771721
Comp9	0.0754469	0.0289274	0.00359270932740808	0.994702336099129
Comp10	0.0465195	0.0195297	0.00221521416461591	0.996917550263745
Comp11	0.0269898	0.008776	0.00128522850116941	0.998202778764915
Comp12	0.0182138	0.0069596	0.00086732376211011	0.999070102527025
Comp13	0.0112542	0.0074181	0.00053591425641764	0.999606016783442
Comp14	0.0038361	0.0017053	0.000182671418585391	0.999788688202028
Comp15	0.0021308	0.0005435	0.000101466661119823	0.999890154863148
Comp16	0.0015873	0.0010828	0.0000755857101536955	0.999965740573301
Comp17	0.0005045	0.0003514	0.000024023808210508	0.999989764381512
Comp18	0.0001531	0.0001097	$7.29047579193018 \times 10^{-6}$	0.999997054857304
Comp19	0.0000434	0.0000251	$2.06666655368889 \times 10^{-6}$	0.999999121523858
Comp20	0.0000183	0.000018152	$8.71428523790479 \times 10^{-7}$	0.99999992952381
Comp21	0.000000148	0	$7.04761866234923 \times 10^{-9}$	1

Factor Loadings				
Variable	Comp1	Comp2	Comp3	
softmax/sigmoid_age	0.06907616	−0.31917403	0.31772215	
softmax/sigmoid_life	0.28152399	−0.01856470	−0.22246703	
softmax/sigmoid_fertility	−0.13845220	0.00299056	−0.65649774	
softmax/sigmoid_gender	−0.08125430	−0.35619030	0.19521063	
softmax/sigmoid_adol	−0.07906722	0.34546407	−0.10625763	
softmax/sigmoid_maternal	−0.18681935	0.22294634	0.38977843	
softmax/sigmoid_contraceptive	0.25441186	0.17277652	0.11979326	
softmax/sigmoid_contraceptivemodern	0.23600066	0.22022469	0.07009891	
softmax/sigmoid_mortality	−0.28592273	−0.01645479	0.05751305	
softmax/sigmoid_literacy_h	−0.23433108	−0.23381394	−0.01939310	
softmax/sigmoid_literacy_t	0.26988757	0.16057109	0.01324774	
softmax/sigmoid_secondary_s	0.29153615	0.00808244	−0.06708010	
softmax/sigmoid_secondary_t	0.29113876	−0.02320071	−0.10636140	
softmax/sigmoid_tertiary	0.21700434	−0.23868564	0.17070596	
softmax/sigmoid_unemp	0.27534489	−0.01724370	0.10967003	
softmax/sigmoid_wage	−0.10792414	0.32631699	−0.02325787	
softmax/sigmoid_selfemp	0.10785336	−0.32627751	0.02357733	
softmax/sigmoid_labor	−0.06318887	0.32056377	0.34914718	
softmax/sigmoid_emp	−0.27087966	0.11870014	0.01271066	
softmax/sigmoid_seats	0.27395420	−0.00067598	−0.08525012	
softmax/sigmoid_law	0.22530913	0.23476799	0.08193170	

Table A4. PCA results.

Method	Bartlett Sphericity Test			Kaiser-Meyer-Olkin Measure of Sampling Adequacy
	Khi-Deux	Degree of Freedom	p-Value	
Normalization with Z-score	66543.042	231	0.000	0.881
Normalization with Min-Max	61921.140	231	0.000	0.863
Normalization with Softmax	67741.160	231	0.000	0.883
Normalization with Sigmoid	67741.155	231	0.000	0.883

Table A5. VIF results.

Variable	Model Using Z-Score		Model Using Min-Max		Model Using Softmax/Sigmoid	
	VIF	1/VIF	VIF	1/VIF	VIF	1/VIF
GDP per capita (log)	1.670	0.597	1.700	0.589	1.680	0.596
Renewable energy (log)	1.580	0.635	1.550	0.643	1.580	0.633
Natural Resource Rents (log)	1.450	0.689	1.460	0.687	1.450	0.690
Total Population (log)	1.240	0.807	1.240	0.808	1.240	0.808
Women's empowerment (log)	1.190	0.842	1.160	0.859	1.180	0.845
International Tourism expenditures (log)	1.050	0.955	1.050	0.954	1.050	0.954
Control of Corruption (log)	1.010	0.994	1.010	0.994	1.010	0.994
Mean VIF	1.310		1.310		1.310	

Table A6. Panel Unit root test: Overall and per quantile.

Panel A: Unit Rot Tests						
In Level	With Constant	With Constant and Trend	With Constant		With Constant and Trend	
Variable	CIPS Statistic	CIPS Statistic	CADF t-bar	CADF Z[t-bar]	CADF t-bar	CADF Z[t-bar]
CO ₂ emissions (in log)	−2.101 *	−2.235	−2.182 **	−2.645 ***	−2.275	0.228
Women's empowerment using Z-score (in log)	−2.529 ***	−2.600 **	−2.571 ***	−5.088 ***	−2.759 ***	−2.934 ***
Women's empowerment using Min_Max (in log)	−2.280 ***	−2.461	−2.514 ***	−4.726 ***	−2.755 ***	−2.907 ***
Women's empowerment using Softmax (in log)	−2.141 *	−2.340	−2.588 ***	−5.191 ***	−2.760 ***	−2.944 ***
GDP per capita (in log)	−1.436	−1.596	−1.786	−0.161	−2.017	1.917
Natural resource rents (in log)	−1.827	−2.253	−2.075 *	−1.974 **	−2.648 **	−2.213 **
Renewable energy (in log)	−1.101	−1.885	−1.370	2.446	−2.099	1.383
Total population (in log)	−1.803	−1.920	−3.088 ***	−8.330 ***	−2.863 ***	−3.615 ***
International tourism expenditures (in log)	−3.170 ***	−3.436 ***	−2.504 ***	−4.665 ***	−2.916 ***	−3.965 ***
Control of corruption (in log)	−1.677	−1.985	−1.550	1.317	−1.852	2.997
In First-Difference	With Constant					
Variable	CIPS Statistic		CADF t-bar	CADF Z[t-bar]		
CO ₂ emissions (in log)	−4.507 ***		−3.257 ***	−9.386 ***		
Women's empowerment using Z-score (in log)	−4.375 ***		−3.222 ***	−9.170 ***		
Women's empowerment using Min_Max (in log)	−4.211 ***		−3.093 ***	−8.359 ***		
Women's empowerment using Softmax (in log)	−4.004 ***		−2.960 ***	−7.526 ***		
GDP per capita (in log)	−3.940 ***		−2.783 ***	−6.414 ***		
Natural resource rents (in log)	−4.405 ***		−3.495 ***	−10.878 ***		
Renewable energy (in log)	−4.267 ***		−3.063 ***	−8.168 ***		
Total population (in log)	−2.053		−2.432 ***	−4.217 ***		
International tourism expenditures (in log)	−5.444 ***		−4.372 ***	−16.381 ***		
Control of corruption (in log)	−4.362 ***		−3.084 ***	−8.301 ***		
Panel B: Quantile Unit Root Test						
In Level	With Constant					
Variable	CIPS Statistic	$\tau = 0.1$	$\tau = 0.25$	$\tau = 0.5$	$\tau = 0.75$	$\tau = 0.9$
CO ₂ emissions (in log)	−2.182 **	−4.075	−1.696 **	−1.777 ***	−1.472	−4.440 **
Women's empowerment using Z-score (in log)	−2.571 ***	−4.606 **	−1.508	−1.991 ***	−2.200 ***	−5.148 ***
Women's empowerment using Min_Max (in log)	−2.514 ***	−3.950	−1.505 *	−2.048 ***	−2.452 ***	−5.254 ***

Table A6. Cont.

Panel B: Quantile Unit Root Test						
In Level	With Constant					
Variable	CIPS Statistic	$\tau = 0.1$	$\tau = 0.25$	$\tau = 0.5$	$\tau = 0.75$	$\tau = 0.9$
Women's empowerment using Softmax (in log)	−2.588 ***	−4.321 *	−1.589 *	−1.996 ***	−2.262 ***	−5.028 ***
GDP per capita (in log)	−1.786	−3.701	−1.194	−1.368	−1.183	−3.102
Natural resource rents (in log)	−2.075 *	−4.413 **	−1.692 **	−1.417	−1.277	−3.663
Renewable energy (in log)	−1.370	−1.447	−0.413	−1.740 **	−1.896 ***	−3.389
Total population (in log)	−1.874	−2.738	−1.726 ***	−1.583 ***	−1.693 ***	−3.411 **
International tourism expenditures (in log)	−2.504 ***	−4.176	−1.663 **	−1.792 ***	−1.647 **	−3.986
Control of corruption (in log)	−1.550	−4.088	−1.103	−1.233	−1.474	−3.773
In Level	With Constant and Trend					
Variable	CIPS Statistic	$\tau = 0.1$	$\tau = 0.25$	$\tau = 0.5$	$\tau = 0.75$	$\tau = 0.9$
CO ₂ emissions (in log)	−2.182 **	−4.038	−1.696	−1.777	−1.472	−4.416
Women's empowerment using Z-score (in log)	−2.571 *	−4.582	−1.508	−1.991	−2.200 *	−5.148
Women's empowerment using Min_Max (in log)	−2.514	−3.925	−1.505	−2.048 *	−2.452 **	−5.254
Women's empowerment using Softmax (in log)	−2.588 *	−4.309	−1.589	−1.996	−2.262 **	−5.028
GDP per capita (in log)	−1.786	−3.677	−1.194	−1.368	−1.183	−3.041
Natural resource rents (in log)	−2.075 *	−4.398	−1.692	−1.417	−1.277	−3.639
Renewable energy (in log)	−1.370	−1.318	−0.401	−1.740	−1.896	−3.353
Total population (in log)	−1.803	−2.640	−1.653	−1.546	−1.632	−3.332
International tourism expenditures (in log)	−2.504	−4.139	−1.663	−1.792	−1.647	−3.938
Control of corruption (in log)	−1.550	−4.052	−1.103	−1.233	−1.474	−3.773
In the First Difference	With Constant					
Variable	CIPS Statistic	$\tau = 0.1$	$\tau = 0.25$	$\tau = 0.5$	$\tau = 0.75$	$\tau = 0.9$
CO ₂ emissions (in log)	−3.257 ***	−5.340 ***	−2.760 ***	−2.877 ***	−2.182 ***	−5.006 ***
Women's empowerment using Z-score (in log)	−3.222 ***	−5.341 ***	−2.910 ***	−2.796 ***	−2.471 ***	−4.952 ***
Women's empowerment using Min_Max (in log)	−3.093 ***	−5.174 ***	−2.605 ***	−2.611 ***	−2.643 ***	−4.996 ***
Women's empowerment using Softmax (in log)	−2.960 ***	−5.264 ***	−2.782 ***	−2.838 ***	−2.289 ***	−5.109 ***
GDP per capita (in log)	−2.783 ***	−5.299 ***	−2.193 ***	−2.601 ***	−1.970 **	−4.514 **
Natural resource rents (in log)	−3.495 ***	−5.622 ***	−2.576 ***	−3.052 ***	−3.156 ***	−5.883 ***
Renewable energy (in log)	−3.063 ***	−2.864 ***	−1.733 *	−3.167 ***	−2.377 ***	−4.953 ***
Total population (in log)	−2.053	−2.457	−1.616 ***	−1.808 ***	−1.432 **	−2.360
International tourism expenditures (in log)	−4.372 ***	−5.827 ***	−3.300 ***	−3.669 ***	−3.227 ***	−5.844 ***
Control of corruption (in log)	−3.084 ***	−4.974 ***	−2.355 ***	−2.958 ***	−2.560 ***	−5.161 ***

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A7. Structural heterogeneity through CCEMG and Instrumental Variables.

Variable	(1)	(2)	(3)
Natural resource rents (log)	0.045 (0.088)	0.112 (0.111)	0.145 (0.103)
Women's empowerment (log)	−0.482 * (0.248)	−0.686 *** (0.266)	−0.536 *** (0.185)
Renewable Energy (log)	−0.667 *** (0.185)	−0.754 *** (0.203)	−0.670 *** (0.160)
Women's empowerment × Renewable Energy (log)	0.228 ** (0.100)	0.298 *** (0.114)	0.249 *** (0.090)

Table A7. Cont.

Variable	(1)	(2)	(3)
Carbon emissions_csa (log)	0.830 ** (0.387)	0.930 ** (0.431)	1.085 ** (0.434)
Women's empowerment_csa (log)	−0.178 (0.155)	−0.067 (0.141)	−0.135 (0.139)
Renewable Energy_csa (log)	−0.003 (0.065)	0.067 (0.076)	0.060 (0.069)
Natural Resource rents_csa (log)	0.015 (0.071)	−0.045 (0.087)	−0.084 (0.076)
constant	1.248 ** (0.622)	1.267 ** (0.607)	1.350 ** (0.548)
Observations	766	766	766
Number of groups	37	37	37

Note: csa: Cross-sectional average. (1): Using Z-score, (2): Using Min-Max, (3): Using Softmax/Sigmoid. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is CO₂ emissions.

Table A8. Distributional Heterogeneity through QCCEMG.

Panel A: Women's Empowerment Using Z-Score						
Variable	Type	$\tau = 0.10$	$\tau = 0.25$	$\tau = 0.50$	$\tau = 0.75$	$\tau = 0.90$
L1 Carbon emissions (log)	Short-run	0.158 * (0.090)	0.143 (0.093)	0.056 (0.104)	0.072 (0.107)	0.059 (0.105)
Women's empowerment (log)	Short-run	−0.406 *** (0.140)	−0.416 *** (0.142)	−0.354 *** (0.127)	−0.176 (0.161)	−0.230 (0.173)
	Long-run	−0.976 *** (0.174)	−0.983 *** (0.173)	−0.711 *** (0.141)	−0.486 ** (0.175)	−0.530 ** (0.186)
Natural resource rents (log)	Short-run	−0.000 (0.046)	−0.003 (0.046)	0.036 (0.053)	0.047 (0.068)	0.069 (0.071)
	Long-run	0.287 *** (0.055)	0.285 *** (0.054)	−0.068 (0.057)	−0.290 *** (0.073)	−0.279 *** (0.076)
GDP per capita (log)	Short-run	0.249 (0.261)	0.229 (0.259)	0.885 ** (0.377)	0.568 (0.353)	0.502 (0.371)
	Long-run	2.466 *** (0.311)	2.446 *** (0.304)	1.762 *** (0.413)	0.754 (0.387)	0.815 * (0.398)
Speed of adjustment	Adjustment	−0.842	−0.857	−0.944	−0.928	−0.941
Half-life	Adjustment	1.350	1.350	1.730	1.230	1.120
Panel B: Women's Empowerment Using Min-Max						
Variable	Type	$\tau = 0.10$	$\tau = 0.25$	$\tau = 0.50$	$\tau = 0.75$	$\tau = 0.90$
L1 Carbon emissions (log)	Short-run	0.240 ** (0.105)	0.252 ** (0.103)	0.083 (0.107)	0.077 (0.114)	0.073 (0.114)
Women's empowerment (log)	Short-run	−0.209 (0.191)	−0.198 (0.200)	−0.141 (0.199)	−0.219 (0.155)	−0.220 (0.155)
	Long-run	−0.874 *** (0.254)	−0.664 * (0.270)	−4.952 *** (0.217)	−0.558 ** (0.171)	−0.573 *** (0.170)
Natural resource rents (log)	Short-run	−0.031 (0.054)	−0.030 (0.055)	−0.014 (0.051)	0.017 (0.070)	0.022 (0.071)
	Long-run	0.343 *** (0.072)	0.327 *** (0.073)	−0.494 *** (0.056)	−0.247 ** (0.075)	−0.241 ** (0.076)
GDP per capita (log)	Short-run	0.118 (0.362)	0.146 (0.368)	0.620 ** (0.271)	0.129 (0.295)	0.126 (0.298)
	Long-run	1.792 *** (0.476)	1.969 *** (0.493)	−6.164 *** (0.306)	−0.595. (0.320)	−0.595. (0.321)
Speed of adjustment	Adjustment	−0.760	−0.748	−0.917	−0.923	−0.927
Half-life	Adjustment	2.280	2.320	1.300	1.680	1.640
Panel C: Women's Empowerment Using Softmax/Sigmoid						
Variable	Type	$\tau = 0.10$	$\tau = 0.25$	$\tau = 0.50$	$\tau = 0.75$	$\tau = 0.90$
L1 Carbon emissions (log)	Short-run	0.213 ** (0.090)	0.200 ** (0.094)	0.134 (0.091)	0.144 (0.099)	0.131 (0.099)
Women's empowerment (log)	Short-run	−0.219 (0.137)	−0.180 (0.159)	−0.090 (0.164)	−0.321 (0.203)	−0.348. (0.205)
	Long-run	1.442 *** (0.176)	0.900 *** (0.200)	0.784 *** (0.190)	−0.627 ** (0.241)	−0.648 ** (0.240)
Natural resource rents (log)	Short-run	−0.044 (0.048)	−0.050 (0.048)	−0.017 (0.053)	0.009 (0.069)	0.028 (0.071)
	Long-run	−0.163 ** (0.061)	−0.103. (0.061)	−0.287 *** (0.062)	−0.351 *** (0.081)	−0.333 *** (0.082)
GDP per capita (log)	Short-run	0.393 (0.395)	0.419 (0.394)	0.345 (0.336)	0.578. (0.314)	0.490 (0.345)
	Long-run	−0.907. (0.505)	−0.803 (0.496)	1.027 ** (0.390)	0.064 (0.375)	−0.014 (0.402)
Speed of adjustment	Adjustment	−0.787	−0.800	−0.866	−0.856	−0.870
Half-life	Adjustment	0.710	0.760	1.340	2.260	2.230
Number of groups	35	35	35	35	35	35

Note: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is CO₂ emissions.

Table A9. Distributional and Conditional Heterogeneity through QCCEMG.

Panel A: Women's Empowerment Using Z-Score						
Variable	Type	$\tau = 0.10$	$\tau = 0.25$	$\tau = 0.50$	$\tau = 0.75$	$\tau = 0.90$
L1 Carbon emissions (log)	Short-run	0.121 (0.088)	0.136 (0.090)	0.181 ** (0.071)	0.146. (0.085)	0.108 (0.095)
Women's empowerment (log)	Short-run	−0.214 (0.261)	−0.279 (0.270)	−0.405. (0.239)	−0.794 ** (0.357)	−0.815 ** (0.358)
	Long-run	−0.448 (0.298)	−0.734 * (0.314)	−0.161 (0.295)	1.653 *** (0.428)	1.449 *** (0.413)
Renewable energy (log)	Short-run	−0.495 *** (0.168)	−0.533 *** (0.174)	−0.754 *** (0.178)	−0.972 *** (0.280)	−1.027 *** (0.287)
	Long-run	−1.125 *** (0.199)	−1.369 *** (0.211)	−1.232 *** (0.232)	−0.932 ** (0.347)	−1.202 *** (0.344)
Women's empowerment × Renewable energy	Short-run	0.092 (0.102)	0.114 (0.105)	0.269 *** (0.103)	0.377 *** (0.142)	0.407 *** (0.146)
	Long-run	0.139 (0.117)	0.260 ** (0.123)	0.279 ** (0.129)	0.065 (0.171)	0.206 (0.171)
Speed of adjustment	Adjustment	−0.879	−0.864	−0.819	−0.854	−0.892
Half-life	Adjustment	1.340	1.450	1.780	1.820	1.810
Panel B: Women's Empowerment Using Min-Max						
Variable	Type	$\tau = 0.10$	$\tau = 0.25$	$\tau = 0.50$	$\tau = 0.75$	$\tau = 0.90$
L1 Carbon emissions (log)	Short-run	0.161. (0.089)	0.168. (0.088)	0.201 *** (0.075)	0.080 (0.093)	0.063 (0.099)
Women's empowerment (log)	Short-run	−0.549. (0.322)	−0.554. (0.320)	−0.597. (0.332)	−0.814. (0.422)	−0.818. (0.427)
	Long-run	−1.161 ** (0.390)	−1.697 *** (0.391)	−1.639 *** (0.422)	7.805 *** (0.468)	7.795 *** (0.465)
Renewable energy (log)	Short-run	−0.673 *** (0.202)	−0.681 *** (0.203)	−0.788 *** (0.268)	−1.027 *** (0.325)	−1.034 *** (0.325)
	Long-run	−1.493 *** (0.256)	−2.332 *** (0.258)	−2.294 *** (0.347)	1.711 *** (0.370)	1.692 *** (0.366)
Women's empowerment × Renewable energy	Short-run	0.178 (0.113)	0.184 (0.113)	0.270 * (0.135)	0.425 ** (0.169)	0.433 ** (0.169)
	Long-run	0.404 ** (0.137)	0.597 *** (0.138)	0.789 *** (0.171)	−0.545 ** (0.189)	−0.536 ** (0.186)
Speed of adjustment	Adjustment	−0.839	−0.832	−0.799	−0.920	−0.937
Half-life	Adjustment	1.340	1.770	1.700	1.570	1.590
Panel C: Women's Empowerment Using Softmax/Sigmoid						
Variable	Type	$\tau = 0.10$	$\tau = 0.25$	$\tau = 0.50$	$\tau = 0.75$	$\tau = 0.90$
L1 Carbon emissions (y)	Short-run	0.188. (0.097)	0.194 * (0.095)	0.190 *** (0.070)	0.029 (0.083)	0.037 (0.083)
Women's empowerment (log)	Short-run	−0.588 * (0.277)	−0.576 * (0.280)	−0.414 (0.275)	−0.701 (0.470)	−0.629 (0.469)
	Long-run	−5.151 *** (0.352)	−5.104 *** (0.357)	−1.320 *** (0.342)	−1.926 *** (0.488)	−1.612 ** (0.490)
Renewable energy (log)	Short-run	−0.535 *** (0.150)	−0.527 *** (0.150)	−0.539 *** (0.159)	−0.749 * (0.348)	−0.754 * (0.355)
	Long-run	−9.165 *** (0.201)	−9.160 *** (0.201)	−2.397 *** (0.205)	−3.249 *** (0.364)	−2.588 *** (0.375)
Women's empowerment × Renewable energy	Short-run	0.174. (0.093)	0.164. (0.093)	0.177. (0.093)	0.316. (0.181)	0.320. (0.185)
	Long-run	3.193 *** (0.117)	3.173 *** (0.118)	0.598 *** (0.117)	0.857 *** (0.188)	0.750 *** (0.194)
Speed of adjustment	Adjustment	−0.812	−0.806	−0.810	−0.971	−0.963
Half-life	Adjustment	9.220	9.220	2.280	2.560	1.980
Number of groups	35	35	35	35	35	35

Note: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is CO₂ emissions.

Table A10. Panel Causality Tests.

A. Causality: Women's Empowerment Using Z-Score → CO ₂ Emissions			A. Causality: Women's Empowerment Using Min-Max → CO ₂ Emissions			A. Causality: Women's Empowerment Using Softmax/Sigmoid → CO ₂ Emissions		
Quantile	Coeff.	Wald	Quantile	Coeff.	Wald	Quantile	Coeff.	Wald
0.10	0.0492	16.971 ***	0.10	0.0421	11.459 ***	0.10	0.0477	18.479 ***
0.25	0.0384	42.881 ***	0.25	0.0354	36.340 ***	0.25	0.0378	44.063 ***
0.50	0.0389	86.343 ***	0.50	0.0354	72.687 ***	0.50	0.0355	86.015 ***
0.75	0.0529	50.130 ***	0.75	0.0504	41.221 ***	0.75	0.0518	55.661 ***
0.90	0.0524	10.283 ***	0.90	0.0480	8.226 ***	0.90	0.0543	12.642 ***
Sup-Wald = 86.343			Sup-Wald = 72.687			Sup-Wald = 86.015		
B. Causality: CO ₂ Emissions → Women's Empowerment Using Z-Score			B. Causality: CO ₂ Emissions → Women's Empowerment Using Min-Max			B. Causality: CO ₂ Emissions → Women's Empowerment Using Softmax/Sigmoid		
Quantile	Coeff.	Wald	Quantile	Coeff.	Wald	Quantile	Coeff.	Wald
0.10	−0.0236	2.245	0.10	−0.0259	2.100	0.10	−0.0240	1.956
0.25	−0.0127	1.324	0.25	−0.0129	1.330	0.25	−0.0127	1.155
0.50	−0.0065	1.209	0.50	−0.0069	0.810	0.50	−0.0077	1.011
0.75	0.0037	0.125	0.75	−0.0007	0.006	0.75	0.0043	0.220
0.90	−0.0022	0.015	0.90	−0.0053	0.069	0.90	0.0099	0.195
Sup-Wald = 2.245			Sup-Wald = 2.100			Sup-Wald = 1.956		

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Critical values at 1%, 13.01, 5%, 9.84, and 10%, 8.19, respectively.

Table A11. Fourier Panel Unit Root Test.

Variable	Model A: Level (Intercept)	Model B: Level (Intercept + Trend)	First Difference (Model A)
CO ₂ emissions (log)	−4.098 ***	−4.819 ***	−6.387 ***
Women's empowerment using Z-score (log)	−4.201 ***	−4.769 ***	−5.807 ***
Women's empowerment using Min-Max (log)	−4.270 ***	−4.757 ***	−5.751 ***
Women's empowerment using Softmax/Sigmoid (log)	−4.122 ***	−4.441 ***	−5.477 ***
GDP per capita (log)	−3.956 ***	−4.757 ***	−5.819 ***
Natural resources (log)	−4.294 ***	−4.441 ***	−6.054 ***
Renewable energy (log)	−4.149 ***	−4.545 ***	−5.720 ***
Population (log)	−3.975 ***	−4.352 ***	−4.677 ***
Tourism (log)	−5.411 ***	−5.959 ***	−7.480 ***
Control of Corruption (log)	−3.935 ***	−4.757 ***	−6.603 ***

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A12. Fourier Bootstrapped Panel Causality Test.

H0: Women's Empowerment Does Not Granger Cause CO ₂ Emissions						
Test	Using Z-score		Using Min-Max		Using Softmax/Sigmoid	
	Statistic	Boot p -Value	Statistic	Boot p -Value	Statistic	Boot p -Value
PFTY (Fisher)	96.109	0.043 **	104.197	0.012 **	89.617	0.104
W-bar	1.7507	—	1.8857	—	1.5544	—
Z-bar	3.2287	0.0012 ***	3.8094	0.0001 ***	2.3845	0.0171 **
Z-bar tilde	2.3555	0.0185 **	2.8442	0.0045 ***	1.6449	0.1000 *
H0: CO ₂ Emissions Does Not Granger Cause Women's Empowerment						
Test	Using Z-score		Using Min-Max		Using Softmax/Sigmoid	
	Statistic	Boot. p -Value	Statistic	Boot. p -Value	Statistic	Boot. p -Value
PFTY (Fisher)	79.291	0.316	79.437	0.312	80.208	0.291
W-bar	1.2361	—	1.2399	—	1.2685	—
Z-bar	1.0153	0.3099	1.0319	0.3021	1.1547	0.2482
Z-bar tilde	0.4926	0.6223	0.5065	0.6125	0.6098	0.5420

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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