

Article

A Validated Multi-Level Human Capital Framework for 4IR-Enabled Innovation Within the WEF Nexus

Oluwadamilola Esan ^{1,2,*} , Nnamdi Nwulu ²  and Omoseni Oyindamola Adepoju ^{2,3} 

¹ Department of Engineering Management, Faculty of Engineering and Built Environment, University of Johannesburg, Johannesburg 2092, South Africa

² Centre for Cyber-Physical Food, Energy & Water Systems (CCP-FEWS), University of Johannesburg, Johannesburg 2092, South Africa; nnwulu@uj.ac.za (N.N.); adepoju.omoseni@luc.edu.ng (O.O.A.)

³ Department of Management and Accounting, Faculty of Management and Social Sciences, Lead City University, Ibadan 200255, Nigeria

* Correspondence: esanoluwadamilola2@gmail.com

Abstract

There has been an increasing need to manage the water, energy, and food (WEF) Nexus in an integrated and sustainable way using Industry 4.0 (4IR) technologies. While 4IR technologies can significantly improve resource management and sustainability in the Nexus, their uptake across the WEF Nexus has been uneven due to institutional fragmentation and limited digital capability. This study assessed a multi-level human capital framework developed to facilitate the structured integration of 4IR technologies into the WEF Nexus. The study leveraged human capital theory and Strategic Human Resource Management to frame capability development as a multi-level process. The study employed a mixed-methods approach, initially surveying 262 professionals in the WEF Nexus to assess essential skill capabilities. This was followed by a two-round Delphi procedure involving 12 experts to refine and validate the multi-level framework. The findings reveal that digital transformation in the WEF Nexus is dependent on the synchronisation of national policy frameworks, organisational learning cultures, and individual skill sets. These levels do not work as separate enablers; instead, they work together as an integrated capacity ecosystem in which misalignment at any point will hinder the effective integration of 4IR technologies. The validated framework provides a systematic approach to understanding the interplay of human capital processes within socio-technical systems and provides a structured approach for designing comprehensive strategies that strengthen digital readiness across sectors. The study advocates for a system-embedded human capital (SEHC) approach and contributes to ongoing discussions on innovation in the public sector by highlighting the systemic nature of human capital development in sustainability- and resource-critical sectors.

Keywords: human capital development; fourth industrial revolution; WEF Nexus; strategic human resource management; sustainable development; resource governance; workforce transformation



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1. Introduction

The growing pressures from climate change, urbanisation, resource scarcity, population growth, and economic development have complicated efforts to manage food, energy and water resources sustainably. This complication is further worsened by the interrelationship between these resources and the need for cross-sectoral integration (Esan et al., 2024) [1]. This complex relationship shows that addressing these resources in

isolation will be ineffective and counterproductive to sustainability goals (Adom et al., 2022; Ghosh et al., 2024; Nhamo et al., 2020) [2–4]. In addition, as demand for these resources increases, the pressure on their availability and other natural resources also increases, especially in vulnerable regions with limited resources, such as Sub-Saharan Africa. As a way to proffer solutions to these challenges, there has been a global drive to adopt the Water–Energy–Food (WEF) Nexus approach to managing these resources and address their interdependencies, especially in developing countries where governance fragmentation, limited infrastructure, and institutional rigidity and bureaucracy limit sustainability (Apeh & Nwulu, 2024) [5]. Although the WEF Nexus has resulted in the development of several models and resource management principles, which have improved cross-sectoral coordination and resource efficiency, implementation has been inconsistent and hindered by weak institutional capacity, silo-based decision-making, and shortages of the skills and manpower necessary for operationalising the WEF Nexus (Esan et al., 2024; Nhamo et al., 2020; Yupanqui et al., 2025) [1,4,6].

At the same time, the fourth industrial revolution (4IR) has been confirmed to provide innovative opportunities for predictive modelling, automation, real-time monitoring, and systems optimisation within various sectors globally, including the WEF Nexus David et al. (2022) [7] and Hair et al. (2017) [8]. In their study, Behuria et al. (2024) [9] and Rajak et al. (2023) [10] affirmed that there has been global evidence in countries like India, Germany, Japan and the Netherlands of how 4IR technologies can improve irrigation efficiency, optimise energy distribution, and improve food production processes. Yet, despite these technological possibilities, developing countries like South Africa continue to struggle with inadequate digital skills, unclear technology adoption pathways, and fragmented policies that limit the successful integration of 4IR innovations into the WEF Nexus.

Several existing studies have examined and developed technical models, governance mechanisms, and sectoral interactions within the Nexus; however, no study has examined these interactions holistically. Instead, these studies prioritise physical systems, technological components, and resource flows, without paying adequate attention to the human capabilities, institutional cultures, and national policies that are required for technology-driven transformation. In the study of Rhouma et al. (2024) [11], the authors stated that the dynamics of the WEF Nexus demand adaptive governance, robust institutional collaboration, and innovative solutions to ensure long-term sustainability, but no study has acted on this. The existing WEF Nexus frameworks and models also treat human capital as an auxiliary element rather than a central driver of innovation. This has resulted in several WEF Nexus organisations remaining ill-prepared to deploy and manage 4IR technologies, leading to project failures, stalled reforms, and an increase in the widening of the already-existing digital capability gap. With the increase in deployment of 4IR technologies, and the global push for WEF Nexus implementation, there is no validated human capital-driven, multi-level framework that examines how governance, organisational culture, and individual digital skills interact or complement each other to enable 4IR integration within the WEF Nexus, especially in developing countries, which is a research gap that this study aims to fill. This absence limits the ability of governments, organisations, and practitioners to coherently design strategies, prioritise investments, and build the human capital needed for long-term sustainability in the WEF Nexus.

With the aim of achieving long-term sustainability and resource effectiveness, this study proposes and validates a multi-level human capital framework for integrating 4IR technologies into the WEF Nexus, an approach that has not been explored in any previous study. The authors of this study acknowledge that the effectiveness of 4IR adoption depends not just on technical availability but also on workforce readiness, institutional readiness, and an enabling governance system. In the study by Melloni et al. (2020) [12], the authors

suggest that implementing 4IR technologies within the WEF Nexus requires collaboration among several strategic and complementary stakeholders. Hence, as organisations and nations struggle to keep pace with the ongoing technological transformation, collaborations through human capital become a defining factor that should be considered at all levels. According to Lenihan et al. (2019) [13], human capital refers to the skills, knowledge, and capabilities of an individual or group of people within a population. Considering the complexities of the WEF Nexus, professionals working in these sectors must possess adequate skills, knowledge, and capabilities to deploy 4IR technologies successfully.

Adom & Simatele (2024) [14], David et al. (2022) [7] and Hair et al. (2017) [8] revealed that there have been fragmented and uncoordinated efforts to strengthen human capital for integrating 4IR technologies into the WEF Nexus. Esan et al. (2024) [1] added to this by stating that there is a disconnect between technological innovation and human capital development. The authors affirmed that human capital remains a vital element in integrating 4IR technologies within the WEF Nexus and across all sectors. The study positions the proposed human capital framework as the outcome of an interconnected system and collaboration between governance, institutions, and professionals, hinging on the human capital theory (HCT) and Strategic Human Resource Management (SHRM). The study argues that human capability is a core enabler of sustainable transformation in the WEF Nexus, as opposed to the prevailing view in existing models and frameworks that attributes technology as the primary enabler. According to Ogedengbe et al. (2023) [15], human resources have been identified as a key enabler of technological and structural changes, particularly those brought about by 4IR. The authors support the affirmations of Aust et al. (2020) [16] and Gunawan & Mikhail (2025) [17], who argued that HRM goes beyond mere resource management. They described it as a critical strategic asset, especially when associated with global institutional objectives such as sustainability, digital transformation, or service innovation.

The multi-level human capital framework proposed in this study consists of three layers that reflect a unified approach integrating three critical dimensions important for sustainable innovation and transformation, which are often treated in isolation: national policy formulation, professional training and development, and organisational culture transformation. It advances previous single-level WEF Nexus models or frameworks by introducing a human capital-driven, multi-level model that is different from existing frameworks that predominantly focus on technical or governance systems. In contrast to other existing studies and already developed frameworks, this study not only introduces a novel human capital ecosystem into the WEF Nexus by looking at digital transformation through the lens of the HCT and SHRM, but it also looks at digital transformation in the Nexus as a multi-level and interdependent system to examine how workforce skills, organisational cultures, and policy alignment jointly shape technological adoption in complex public-sector organisations. This study will seek to address the following research questions:

1. How do national policies, organisational culture, and individual competencies influence the integration of 4IR technologies within the WEF Nexus?
2. How do experts assess and refine the practical relevance of a multi-level human capital framework for 4IR integration within the WEF Nexus?

This research is divided into six sections, where Section 2 will discuss the theoretical framework for this study, leveraging HCT and SHRM, Section 3 will describe the methodology adopted for the study, Section 4 will discuss the results of the Delphi analysis, and Sections 5 and 6 will discuss the implications and conclusion of the study.

2. Theoretical Framework

This study adopts a theory triangulation approach to integrate the HCT and the SHRM in governing 4IR technologies within the WEF Nexus. The human capital theory, propounded by Gary Becker, posits that individuals' skills, knowledge, and abilities are valuable economic assets that, when improved through investments in education and training, can increase productivity, innovation and economic growth (Wuttaphan, 2017) [18]. Although the theory was developed initially as an educational theory, it has become prominently applied among economists and social scientists, who have continued to implement it as a guide for policies designed to promote economic growth and skill development (Leoni, 2023) [19]. According to Marginson (2019) [20], the central concept of the theory suggests that investments in training, skills, and abilities can enhance workforce capabilities, which in turn contribute to both organisational success and personal development. This study leverages this central tenet to imply that the adoption of 4IR technologies is directly dependent on the skill sets and competencies of the workforce responsible for deploying these technologies, which is the rationale of this study. This study posits that without targeted skill development, it may be difficult for WEF Nexus organisations and nations to successfully harness the benefits of 4IR technologies in the Nexus, highlighting human capital as a critical driver and strategic asset for innovation and sustainability in managing water, energy, and food resources. This study acknowledges that the classical HCT has been critiqued for overemphasising individual capacity without adequately making provisions for externalities that determine how skills are developed, utilised, and rewarded (Auerbach & Green, 2024) [21]. Choudhury (2022) [22] also argued that the linear assumption of the HCT that automatically equates improved skills and competencies with productivity and economic growth may not always be applicable. This study stands on the argument and affirms that improved skills development may not yield instant or commensurate productivity and innovations, especially in the public sector and complex industries where there is a lot of bureaucracy, limited resources, organisational rigidity, and fragmented decision-making.

To address the limitation of the HCT, the study adopts the SHRM as a complementary framework to link human capital to organisational strategy, culture and performance. According to Wright & McMahan (1992) [23], the authors described SHRM as the pattern of planned human-resource deployments and activities that enable an organisation to achieve its goals. The SHRM positions people and human capital as a strategic resource that is influenced by organisational practice and leadership. It reinforces the affirmation that organisations can only benefit from technological innovations when HR practices, leadership structures, and organisational cultures actively support learning, experimentation, and digital transformation (Cao et al., 2025; Leso et al., 2022) [24,25]. The organisational focus of SHRM complements the individual focus of the HCT and provides a basis to examine human capital in the WEF Nexus, not just from an individual perspective but from a multi-level view, acknowledging that individual human capital is influenced by systemic elements.

Unlike other socio-technical theories, such as the multi-level governance framework or institutional theory, the HCT and SHRM are primarily focused on human capability. Many existing theories have diluted the focus on human capital, overemphasising user attitudes or position transformation as a macro-level socio-technical evolution rather than a capability-driven process. By integrating HCT and SHRM, this study advances two theoretical positions, which are: (1) Technological transformation is fundamentally a human capital-driven process. It is people, not technologies, who drive the success or failure of 4IR initiatives. (2) There is a need for a new system-embedded human capital

theory (SEHC) that acknowledges human capital within an interdependent or interrelated system like the WEF Nexus. Figure 1 shows the theoretical framework for this study.

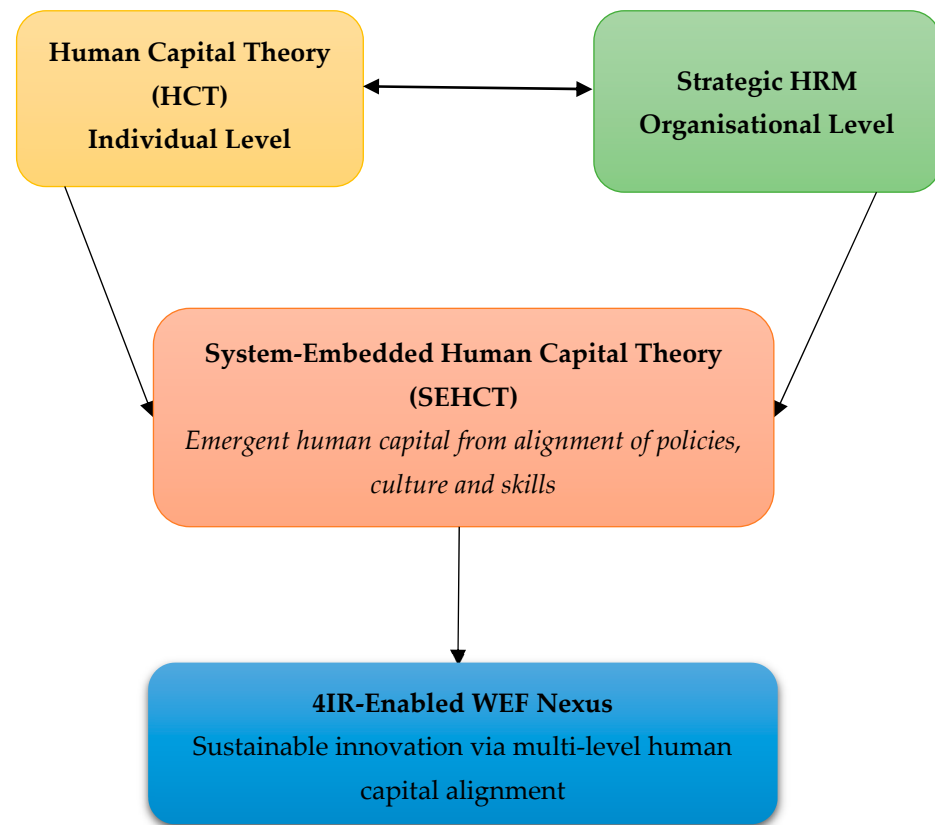


Figure 1. Theoretical framework. Source: Author’s diagram (2025).

3. Review of Existing Frameworks in WEF Nexus

The WEF Nexus is a global initiative proposed to combat the multifaceted challenges of global water, energy, and food. In pursuit of achieving the WEF Nexus objective, several frameworks, models, and methodologies have been proposed and evaluated for operationalisation. The authors of existing frameworks have taken different stances in their operationalisation of the WEF Nexus, ranging from technical models, measurement and analytical tools, sectoral models, governance and policies, synergies and trade-offs, sustainability indicators, financing models, data management and case study applications (Jacobson, 2022; Kabeya et al., 2022; Karabulut et al., 2018; Martinez-Hernandez et al., 2017; Walker et al., 2022) [26–30]. In the framework developed by Mabhaudhi et al. (2021) [31], the authors created a framework for operationalising South Africa’s WEF Nexus, linking it to SDGs 2, 6, and 7. While this framework was designed specifically for South Africa, bridging the gap in regional applicability of frameworks, it focuses mainly on the drivers of SDGs 2, 6, and 7 and how feedback and communication among WEF sectors can improve the performance of the WEF Nexus. The framework, however, fails to acknowledge the role of human capital dynamics in achieving communication, collaboration and sustainability. The proposed framework in this study extends beyond mere sectoral collaboration to introduce an interlinked structure of national policies, organisational culture, and individual digital competencies, shifting the emphasis from resource feedback loops to capability alignment. It considers these elements as codependent drivers of effective collaboration and sustainability.

D’amore et al. (2022) [32] also developed an artificial intelligence (AI) model for WEF Nexus resource management. The study recognised the role of AI in enhancing resilience and sustainability in the WEF Nexus. The study, however, concluded that there

is a need for multi-level analyses and multi-stakeholder involvement in the WEF Nexus. Again, the study was limited to the application of artificial intelligence in the WEF Nexus. In a similar study, Okonkwo et al. (2023) [33] presented a first multi-level approach to energy–water–food (EWF) resource management in their study. The study proposed the molecular, process, and governance levels to address EWF Nexus-related challenges. The molecular level depicted the individual resource level, the process level represented the sectoral synergies and interlinkages, and the governance level depicted the legislation level regulating the internal and external factors influencing the Nexus. The study discussed how communications among these three levels can impact the performance and decision-making process in the Nexus using nanomaterials within the Nexus. These studies establish the benefits of 4IR technologies within the Nexus. However, both D’amore et al. (2022) [32] and Okonkwo et al. (2023) [33]’s frameworks are technocentric and focus on what technologies can do in the Nexus, rather than how systems and people can enable them. While Okonkwo et al. (2023) [33] made an attempt to develop a multi-level framework, the framework was focused on the use of nanomaterials alone, while neglecting the benefits of holistically integrating 4IR technologies in the Nexus.

Additionally, the framework addresses interactions among physical and governance systems; however, it neglects the human capital element through which skills, institutional learning and cross-sectoral collaboration can drive innovation and sustain system performance. The study argues that multiple 4IR technologies will hold tremendous benefits for the WEF Nexus compared to the restricted use of specific technologies. Therefore, a targeted approach is needed to integrate the 4IR technologies across the WEF Nexus and develop a structured approach by which these technologies could be introduced in the Nexus, leveraging the role of the multiple stakeholders involved in the Nexus.

Ekpo et al. (2018) [34] stated that training and organisational culture are factors influencing human capital development. However, this study posits that individual training, and organisational culture alone cannot close the 4IR skills gap. It requires a synergistic strategy incorporating supportive national policies. This study, therefore, advances the framework of Ekpo et al. (2018) [34] and advocates for a more comprehensive, multi-level framework incorporating national policy as an additional component. Considering the importance of WEF resources to economic stability and sustainability, government policies and regulations are crucial for ensuring that organisational practices and training initiatives are aligned with national development objectives. Leveraging the human capital theory and the human capital conceptual framework developed by Ekpo et al. (2018) [34], this study, therefore, proposes that developing individual skills, nurturing conducive organisational cultures, and implementing supportive national policies are critical to operationalising 4IR solutions in the WEF Nexus.

Icpac (2018) [35] proposed a capacity-building framework for the water sector in Kenya. The framework focused on building skills and knowledge through curriculum development at various levels, ranging from trainee technicians to junior professionals. The framework enables them to address complex challenges in resource management. By focusing on skills development, the proposed framework was intended to ensure that the workforce is well-prepared with technical and managerial skills to combat water resource challenges in the country. While this framework serves as a blueprint for capacity building, it faces limitations as it addresses traditional skills gaps, with limited attention to modern technological skills like data analytics, AI, or the IoT, which are crucial for 4IR. Its narrow focus on junior professionals and technicians also overlooks the need for an inclusive capacity-building approach across senior professionals. Additionally, the framework was centred on the water sector. It also lacked the flexibility and inclusivity needed to be adopted across the WEF Nexus, which could hinder the operationalisation of 4IR solutions

in the WEF Nexus. There has not been any human capital development framework for 4IR-enabled WEF solutions through a structured approach in South Africa.

Based on the deductions of prior studies, this study's authors identify a critical gap in addressing the human capital necessary to support 4IR-enabled WEF solutions in South Africa. The essential role of skilled human resources in driving innovations and sustainability in the WEF Nexus has been overlooked, as there has been no structured approach to developing the skills and competencies required to adopt 4IR technologies within the WEF sectors successfully. This gap implies that the WEF Nexus workforce may remain unprepared and incapable of harnessing and sustaining the technological innovations required to effectively integrate 4IR technologies in achieving sustainable WEF Nexus goals. This study will, therefore, bridge this research gap by developing a human capital framework for the South African WEF Nexus, leveraging the work of D'Amore et al. (2022) [32] and Okonkwo et al. (2023) [33]. The proposed framework developed by this study will explore the 4IR technologies that can be integrated into the WEF Nexus, leveraging the roles of individual skills, organisational culture, and national policies to foster 4IR-enabled solutions within the WEF Nexus. Unlike other existing WEF–4IR models that typically emphasise either technology deployment, governance coordination, or skills development in isolation, the proposed framework will be more practically oriented because it specifies an implementable alignment pathway across the three capability layers that most often determine delivery in the public sector: national policy, organisational culture, and workforce competencies. The study also introduces a system-embedded human capital that links technology within the individual, institutional and policy ecosystem, a critical gap that has not been examined by previous studies.

4. Methodology

4.1. Research Design

This study employed a qualitative, exploratory design using the Delphi technique to gather expert consensus on the proposed framework. Chan (2022) [36] and Hair et al. (2022) [37] stated that the Delphi technique is a structured method for achieving consensus among experts through iterative rounds of surveys and feedback. Beiderbeck et al. (2021) [38] also opined that the Delphi technique is a systematic approach for arranging and overseeing structured discussions intended to produce insights regarding present or future issues, particularly when information is scarce. The Delphi technique used in this study provided critical qualitative insights that enriched the framework's development and practical relevance. This study adhered to the conventional framework of the Delphi method, which includes a series of organised rounds to seek expert opinion and achieve a consensus on the proposed framework. According to Ismail & Taliep (2023) [39], the Delphi technique facilitates iterative structured engagement with a panel of experts through multiple survey rounds. The study, however, utilised the e-Delphi method, where a structured questionnaire containing the proposed framework was sent via email to seek expert opinion (Shinners et al., 2021) [40]. The e-Delphi method was utilised to allow for faster survey time and enhance the anonymity of respondents. After each round, participants receive anonymised feedback, enabling them to reflect on and refine their responses. According to Beiderbeck et al. (2021) [38], the process supports the gradual convergence of opinions, making it well-suited for validating this framework.

4.2. Initial Framework Development

The proposed framework was developed following a survey research design that employed a structured questionnaire administered to 262 South African WEF Nexus pro-

professionals. Based on the theoretical framework of the study, the following hypotheses were developed to guide the quantitative analysis:

H1. *National policy alignment has a positive and significant association with the integration of 4IR technologies within the WEF Nexus.*

H2. *Organisational culture has a positive and significant association with the integration of 4IR technologies within the WEF Nexus.*

H3. *Individual competencies and digital skills have a positive and significant association with the integration of 4IR technologies within the WEF Nexus.*

The survey adopted a purposive and snowballing sampling technique to select professionals with adequate knowledge and experience within the South African WEF Nexus. The professionals were selected from the Department of Water and Sanitation (DWS); Gauteng Department of Agriculture, Rural Development, and Environment; Department of Agriculture, Land Reform, and Rural Development, Pretoria; South African National Energy Development Institute (SANEDI); Association of Municipal Electricity Utilities (AMEU); South African Wind Energy Association (SAWEA); Department of Mineral Resources and Energy (DMRE); City Power Johannesburg; and Jo'burg Water and Energy and Electricity Service, Tshwane. Of the respondents who participated in the proposed framework survey, 51.6% had worked for one (1) to ten (10) years, while 48.4% had worked for over 10 years in the South African water, energy or food sectors. In total, 39% of the respondents worked in the water sector, 33.5% were food and agriculture professionals, and 27.6% were experts from the energy sector. The survey questionnaire used Likert-scale items to capture the professionals' agreement levels to various constructs proposed for human capital development within the WEF Nexus. The data collected was analysed using a bootstrapping analysis of Partial Least Squares Structural Equation Modelling (PLS-SEM). PLS-SEM was employed as the initial method to develop the framework, identifying and quantifying the relationships between national policies, organisational culture, and individual-training within the Water–Energy–Food (WEF) Nexus. The framework identified three intervention levels: (1) national policies to be implemented, (2) individual training modules for professionals, and (3) organisational culture to be incorporated within WEF Sectors. The proposed framework takes a different perspective from many existing WEF Nexus frameworks by shifting the analytical centre from Nexus interactions and resource trade-offs to the capability conditions required to operationalise solutions at scale. While many WEF frameworks prioritise modelling interdependencies, synergies, and trade-offs across the water, energy, and food sectors, this framework specifies the human and organisational requirements that determine whether such integrated strategies can be implemented consistently. The result from the survey revealed that national policies take precedence and exert a stronger influence on technological innovation within the WEF Nexus. At the same time, individual professional training plays a more significant role than organisational culture transformations. The hypotheses were empirically examined and validated using PLS-SEM.

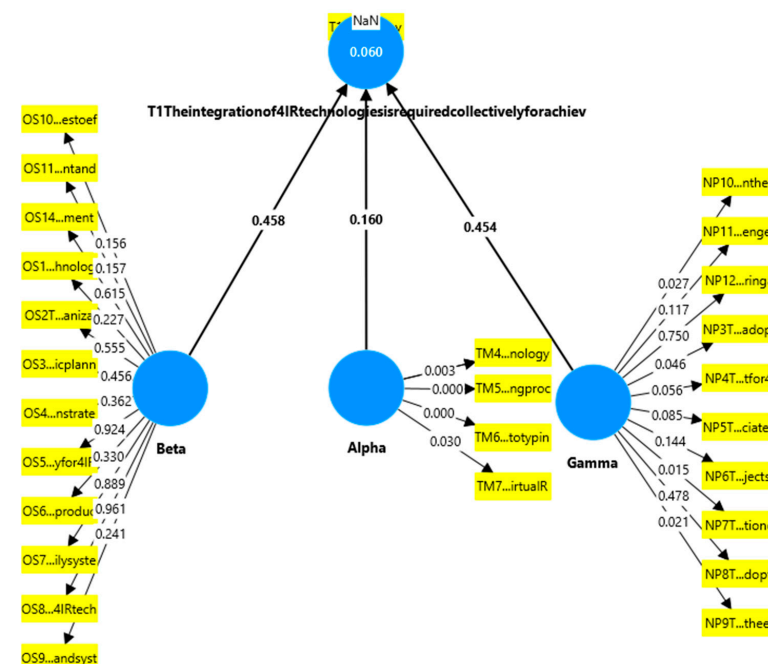
The structural model of the initial framework was assessed using the VIF values to ensure that there was no bias due to collinearity issues. Table 1 revealed no collinearity issue between the exogenous constructs, as all VIF values were less than 3.3, as stated by Hair et al. (2022). [37] The result also revealed that the SRMR value is 0.122, and the NFI value is 0.937. Hair et al. (2017) [8] stated that the SRMR value of an inner model should be less than 0.08 and the NFI value more than 0.90 to guarantee a good model fit. The SRMR and NFI for this study fall within the stipulated values, indicating that the model is a good fit (GoF).

Table 1. Collinearity statistics (VIF) and model fit (internal model).

	VIF
Alpha -> FOURIRTECH	1.948
Beta -> FOURIRTECH	2.034
Gamma -> FOURIRTECH	1.111
SRMR	NFI
0.122	0.937

Source: Research survey (2024) through SmartPLS 4.

A bootstrapping analysis was implemented to test the hypothesis and ascertain the path coefficient and its associated t -value for all direct relationships. The results of the analysis revealed that the three hypotheses proposed in this study are significant and positive: individual-training modules ($\alpha = 0.160$, t -value = 2.105, $p = 0.036$), organisational culture ($\beta = 0.458$, t -value = 2.503, $p = 0.012$), and national policies ($\gamma = 0.454$, t -value = 3.006, $p = 0.003$). Cheah et al. (2017) [41] and (Kock, 2016) [42] stated that the decision rule for hypothesis testing in SmartPLS is (t values > 1.96, $p < 0.05$). This decision rule was also reaffirmed by Savitri et al. (2021) [43] and Zeng et al. (2021) [44]. Following these affirmations, Hypotheses H1, H2, and H3 were substantiated and accepted in this study. Figure 2 shows the direct relationship between the research constructs.

**Figure 2.** Combined effect of research variables. Source: Research survey (2024).

Following the ranking and significance level revealed by the bootstrapping analysis, the study went further to analyse the individual human capital development effort under national policies, individual-training and organisational culture using importance–performance map analysis. All constructs (α = adopting individual-training modules, β = incorporating 4IR into the WEF organisational culture and γ = aligning national policies) are of significant importance ($\alpha = 76.017$, $\beta = 74.959$ and $\gamma = 77.672$), with national policies exerting the most influence, followed by individual-training modules. Under the national policy framework, NP7 and NP4 have the highest importance (NP7 = 78.244, NP4 = 78.053), which means that significant efforts should be put into public–private

partnership and national frameworks that address data management to integrate 4IR-enabled solutions in WEF Nexus. Under organisational culture, OS10 = 76.463 and OS3 = 74.809 are of the highest importance, revealing that WEF organisations should invest in employee training programmes and involve key stakeholders in the strategic plan to foster 4IR-enabled solutions in the WEF Nexus. Similarly, in individual training modules, WEF Nexus professionals should focus on acquiring skills related to big data analytics (TM3 = 79.198) and robotics and automation (TM8 = 78.531). The IPMA provided an additional understanding of the relative importance of each construct with statistical importance metrics, which will facilitate targeted approaches or efforts to constructs of higher importance beyond model assessment. The results of the importance–performance map analysis were used to develop the initial framework, based on the importance–performance analysis of each construct. Figure 3 presents the initial proposed framework.

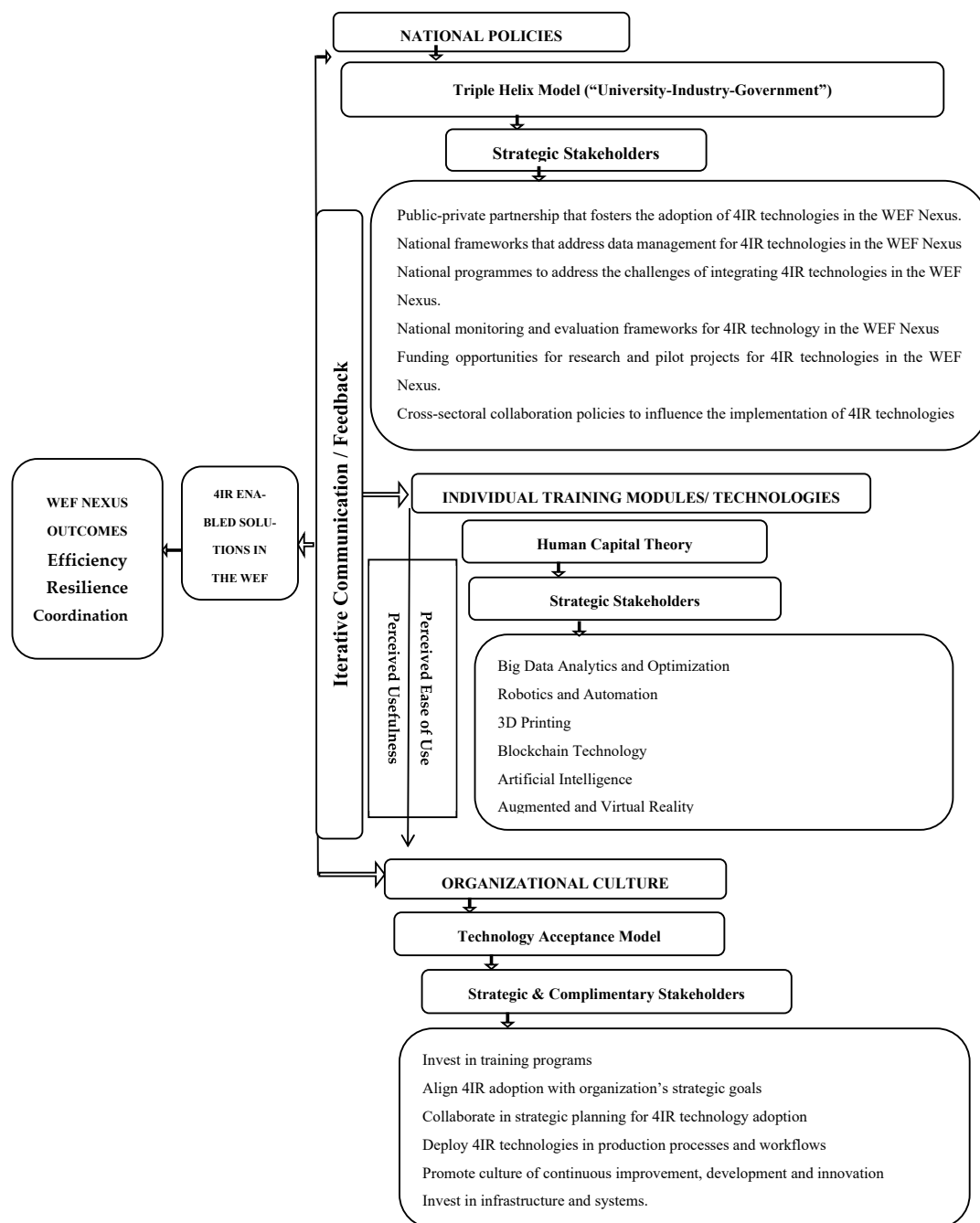


Figure 3. Proposed multi-level human capital development framework.

4.3. Assessment of Proposed Framework Using the Delphi Technique

4.3.1. Panel Selection Criteria and Profile

The experts and professionals who participated in this Delphi study to assess the credibility of the proposed framework were purposively selected within the WEF Nexus in South Africa using criterion sampling. Memon et al. (2025) [45] stated that criterion sampling is a purposive sampling technique where participants are selected based on pre-defined criteria for addressing research questions or objectives. This sampling technique was employed to ensure that only individuals with relevant experience and knowledge contribute to the consensus-building process. Campbell et al. (2020) [46] stated that criterion sampling enhances the credibility, depth and relevance of data collected as participants are qualified to provide informed judgements. This study considered criterion sampling appropriate because Delphi studies rely on expert opinion and insights rather than statistical representation. Therefore, selecting professionals and experts who meet pre-defined criteria as panellists is essential to produce valid outcomes and consensus for this study. The participant recruitment was accomplished via email, inviting experts to participate in the e-Delphi study. Skulmoski et al. (2007) [47] in their study recommended that Delphi panellists or experts must meet four criteria, which include that participants should have a strong understanding and experience in the research area, be open to engaging in the study, have sufficient time to take part in the research and participate in multiple rounds if necessary, and be effective communicators who can share their thoughts and feedback clearly and with few difficulties. Similarly, Hallowell & Gambatese (2010) [48] opined that experts are required to meet at least four of the following criteria: having authored multiple peer-reviewed publications in the research area, delivered a presentation at a conference on the research objective, serving or served as a chair or member of a committee, possess a minimum of five years of relevant working experience, be a faculty member at an accredited higher education institution, hold an advanced academic qualification in a related field, and be registered with a professional organisation. Based on the sampling techniques employed by the study, all participants who were invited for this Delphi study met a minimum of five criteria, including (a) at least five years of experience working in the Water–Energy–Food sectors in South Africa; (b) affiliation with academic, government or industry-based organisations involved in WEF Nexus projects; (c) direct involvement in the water, energy or food sectors; (d) previous participation in the initial survey to develop proposed framework; (e) willingness and availability to engage in multiple Delphi rounds using surveys via email; (f) possess effective communication skills; (g) authorship of not less than five (5) peer-reviewed articles in Scopus high-impact journals; and (h) have occupied or are currently occupying a managerial or strategic position in the water, energy or food sector.

A total of 31 professionals and experts were contacted for the study. However, only 12 participants confirmed their interest and availability to participate in the Delphi process. Chan (2022) [36] and Hair et al. (2022) [37] and Ismail & Taliep (2023) [39] stated that at least eight to ten respondents should be panellists for a Delphi consensus. Okoli & Pawlowski (2004) [49] and Oxley et al. (2025) [50] affirmed that the ideal size for a Delphi panel typically varies from 10 to 18 participants. However, Nasa et al. (2021) [51] argued that there is no standard number of panellists for a Delphi technique. Nordin et al. (2012) [52] further emphasised that the Delphi technique does not call for the expert panels to be representative samples for statistical purposes. The author stated that representation for the Delphi study is assessed by the qualities of the expert panel rather than its number. Hence, having 12 participants participating in this Delphi panel is deemed appropriate. The 12 professionals and experts who participated in the Delphi study represent a diverse range of stakeholders and institutions, including universities, national research bodies, and regulatory agencies. Their varying backgrounds were selected to enrich the Delphi process, ensuring well-rounded information for assessing

the proposed multi-level human capital framework for 4IR innovations in the WEF Nexus. The experts' qualities also contribute to the credibility and depth of the Delphi findings. Although the panellist selection was expert-driven, the demographic distribution reveals a sectoral and gender imbalance, with the majority of the panellists being affiliated with the energy sector, and only 25% being female. This sectoral and gender imbalance may have influenced the consensus on certain dimensions of digital transformation and human capital development, which may affect the framework's composition and the generalisation of the framework from the opinion of the water and food professionals. These imbalances can also affect how the findings are interpreted and extrapolated beyond South Africa, because participant composition may systematically shape which constraints are perceived as most binding and which interventions are prioritised, thereby influencing the relative emphasis placed on policy instruments, organisational enablers, and competency pathways within the framework. The limited female representation may also reduce sensitivity to gender-differentiated barriers in skills access, retention, leadership progression, and technology adoption environments. This means that while the framework offers useful analytical insight, the salience and ranking of its components may shift in countries with different WEF institutional arrangements, skills ecosystems, labour market structures, and gender norms. This study proposes that future studies can set quotas or benchmarks before selection to mitigate against these biases. Additionally, future studies should include independent panellists from other Sub-Saharan African countries who did not participate in the initial framework development, to improve generalizability.

4.3.2. Number of Rounds

Expert opinions were gathered from two (2) rounds of the e-Delphi study through an online survey and adhered to the ethical guidelines of the University. Niederberger & Spranger (2020) [53] stated that two or three rounds are generally adequate for most Delphi studies. Nasa et al. (2021) [51] emphasised that most responses are consolidated in the first two rounds, with minimal changes seen thereafter. This assertion was corroborated by Schmalz et al. (2021) [54], who argued that the most significant responses are obtained in the second round of the Delphi study. Following these assumptions, this study adopted the two-round Delphi consensus for assessing this framework, following the assertions of Barrios et al. (2021) [55] and Shang (2023) [56]. Additionally, this study found that all framework variables achieved consensus in the second round; hence, there was no need to proceed to a third round. The study, therefore, stopped at the second round based on the convergence of the consensus score. Figure 4 reveals the framework validation process.

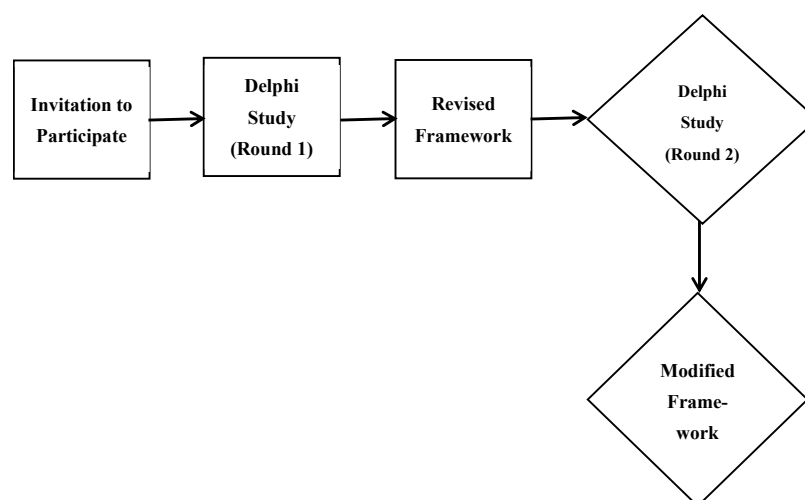


Figure 4. Framework validation process. Source: Author's diagram (2025).

4.3.3. Data Collection and Consensus Measurement

The data was gathered through Google Forms, and the analysis was conducted using IBM SPSS v 29. In the first round, the questionnaire comprised both open-ended and closed-ended questions, allowing experts to evaluate the proposed framework and provide their suggestions and opinions. Participants were asked to rank their agreement regarding the relevance of the policies and modules included in the framework. The close-ended questions utilised a 5-point Likert Scale, where 5 represented “very high relevance” and 1 signified “not relevant”. The feedback from the first round, which included the responses from all participants, was anonymised and sent back to the experts. This anonymised report enabled the experts to review and reconsider their opinions in line with the controlled-feedback principle of the Delphi consensus technique (Barrett & Heale, 2020; Barrios et al., 2021; Hirschhorn, 2019) [55,57,58]. The policies and modules that achieved consensus were noted in the report, alongside the suggestions from the first round, which were highlighted for the experts to review. The responses and suggestions from Round 1 were used to modify the framework and develop an updated questionnaire for Round 2. It was sent to the experts for their ratification and further review. All the constructs in the modified framework achieved consensus in Round 2 and were therefore used for the final ratification of the modified framework. This validation process helped refine the initial PLS-SEM model, offering insights into the real-world alignment of the constructs and suggesting adjustments based on expert judgement.

The Delphi consensus measures the extent of agreement among respondents regarding a specific criterion or variable (Barrios et al., 2021) [55]. Sharma et al. (2021) [59] and Thorn et al. (2021) [60] stated that the consensus for each criterion should be determined based on the calculated mean value, standard deviation, and the percentage of respondents who agreed on that criterion. Chan (2022) [36] and Hair et al. (2022) [37] stated that for a 5-point Likert scale, consensus should be ascertained by a mean value of 3.00 or higher and a consensus rate of 75% or more, whereas Baliga et al. (2024) [61] argued that consensus was achieved when consensus reached a minimum of 80%. The consensus strength was calculated using the consensus formula as stated by Hernández-Leal et al. (2022) [62], given as follows:

$$Cc = (1 - \frac{Vn}{Vt}) \times 100 \quad (1)$$

where

Vn is the number of negative votes (a score of lower than 4);

Vt is the total number of votes.

On the other hand, Nejati et al. (2025) [63] and von der Gracht (2012) [64] stated that consensus can be reached when the interquartile deviation (IQD) is less than or equal to 1, where the interquartile deviation was calculated as follows:

$$\frac{(Q3 - Q1)}{2} \quad (2)$$

where

Q3 = Third Quartile

Q1 = First Quartile

Based on the various consensus mechanisms, the consensus agreement for this study was established using the following methods as shown in Table 2:

Table 2. Consensus rating for the study.

S/N	Consensus Strength	Mean Score	Interquartile Deviation	CC
1	Strong	≥ 4.5	0	$\geq 80\%$
2	Good	≥ 4	≥ 0.5	≥ 75
3	Weak	< 3	≤ 1	< 70

Source: Author's compilation (2025).

4.3.4. Ethical Considerations, Validity and Reliability

This Delphi study obtained ethical approval from the ethics committee and adhered to ethical principles. All study participants participated voluntarily, and informed consent was sought, ensuring that participants fully understood the purpose and procedures of the study. The study also ensured the anonymity of all participants throughout the Delphi rounds. This was done to protect the experts' identities and minimise bias, thereby reducing the risk of the bandwagon effect and enhancing the authenticity of responses. The study also ensured fairness in participant selection, adhering to pre-defined criteria. Additionally, the iterative nature of the Delphi method allowed participants to reflect and revise their responses freely, promoting respect for diverse opinions and upholding academic integrity. The PLS-SEM results, which were used as a basis for the Delphi technique in this study, served to establish the foundational relationships within the framework, while the Delphi validation ensured these relationships were relevant and applicable to the real-world challenges in the WEF Nexus. The result of this study, however, does not suggest a causal relationship between the constructs but rather reveals the priority of each construct in enabling the integration of 4IR technologies within the WEF Nexus.

5. Results

5.1. Description of Delphi Panel

Table 3 reveals the demographic characteristics of the experts and professionals who served as panellists for this Delphi consensus study. The result revealed that most respondents were male (66.7%) while 25% were female. This demonstrated diversity and a balanced perspective of opinions from panellists. The result also indicated that 50% of the panellists were 45–54 years of age, while 25% were within the age bracket of 35–44 years. 58.3% of the panellists have a Doctorate qualification (PhD), while 43.3% have a master's degree. A large percentage of the panellists were affiliated with the energy sector (58.3%), while 25% worked in the Agri-food sector and 16.7% were affiliated with the water sector. A total of 91.6% of the respondents have worked in the WEF sectors for over six (6) years. This demographic distribution revealed an array of highly qualified professionals with postgraduate degrees and a broad range of professional experience. The demographic distribution also strengthens the validity of the study, as panellists consist of professionals who possess the ability to contribute significant input to the study.

5.2. Delphi Round 1 Analysis

The first round of the Delphi consensus was used to assess the designed framework. The framework comprised three levels of influence, from national policies to individual training and organisational culture. The results from the first round, as shown in Table 4, revealed that five of the variables in the framework did not achieve consensus, as their consensus rating was below 80. While the panellists were generally optimistic about the framework, some expressed perceived gaps in the relevance and sequencing of the framework structure and constructs. One participant said, "It will be great if it's supported

by all and adequately implemented". Another panellist affirmed that *"This framework is highly recommended"*. However, two of the panellists shared the same opinion that the framework should be re-ordered. One of them stated that *"the framework should be re-ordered to start from individual to organisation and national level or vice versa"*. The results from the first round also revealed significant content gaps in individual training as the panellists pointed out the absence of digital literacy, Internet of Things (IoT) and cybersecurity modules, which they perceived as widely accepted skills for integrating 4IR technologies. The panellists stated that *"digital literacy training and cybersecurity should be included for professionals as this is the basis of 4IR"*. Additionally, the results from Round 1 also revealed a gap in the prioritisation of cross-sectoral collaborations and the absence of curriculum amendment in the national policies. The panellists said, *"I think the most important policy for the national level should be first to amend our education curriculum and enact cross-sectoral collaboration policies"*. One panellist also stated, *"We can have a governing body or committee to oversee 4IR technology adoption in the sectors"*. Results from the round revealed that panellists considered cross-sectoral collaboration policies and curriculum amendment to be the most important policies to be enacted at the national level to facilitate the integration of 4IR technologies within the WEF Nexus. Consequently, based on the results of the first round, the panellists' suggestions and opinions were implemented to re-order the sequencing of the framework to reflect a top–bottom hierarchical structure and the prioritisation of strategic policies and modules. The Delphi panel confirmed the priority of national policies. It also revealed the need for curriculum reform and enhanced cross-sectoral collaboration, reinforcing the importance of the constructs identified by PLS-SEM.

Table 3. Demographic distribution of consensus panellists.

Demographic Distribution		Frequency	Percentage
Gender	Male	8	66.7
	Female	3	25
	I prefer not to say	1	8.33
Age	25–34	2	16.7
	35–44	3	25
	45–54	6	50
	Above 54	1	8.3
Educational Qualification	Honours	1	8.3
	M.sc	4	33.3
	PhD	7	58.3
Industry of Affiliation	Energy Sector	7	58.3
	Water Sector	2	16.7
	Agri-Food	3	25
Years of Experience	1–5 years	1	8.3
	6–10 years	6	50
	11–15 years	5	41.7

Source: Research survey (2025).

5.3. Delphi Round 2 Analysis

The second round of the Delphi study integrated the feedback and comments from the results of Round 1 to develop a modified framework that was assessed by the panellists. The modified framework includes new skills such as digital literacy and the Internet of Things (IoT) in the individual-training sections. The round two consensus

also assessed the refined national policies, including curriculum realignment and establishing a 4IR-WEF Nexus commission to oversee the integration. The responses from the second round were analysed and rated using the same consensus rating as Round 1, and all the constructs achieved consensus, as seen in Table 5. The consensus rating revealed that the mean score ranked between 4.00 and 4.98. The interquartile deviation was between 0 and 1, while the consensus score was between 80 and 95. All the elements of the framework satisfied the pre-determined consensus rate as stated in Table 1 and, therefore, were considered fit to be included in the framework. For the second round opinion, one of the panellists stated that the framework had been improved, as she affirmed that *“this looks more acceptable than the first framework”*. Another panellist expressed satisfaction with the modified framework, stating that *“this framework should be recommended to the government”*. The assertions of the panellists affirmed that the modified framework was considered comprehensive and relevant for the integration of 4IR technologies in the WEF Nexus, and since all the elements achieved consensus, the Delphi round was closed after the second round, with the modified framework adopted.

Table 4. Results from Round 1 Delphi consensus.

	Mean	Interquartile Deviation	Cc
Public–Private Partnerships	4.92	0	90
Data Management System	4.92	0	60
Education Programmes & Workshops	4.58	0.5	90
National Feedback Systems	4.75	0.5	85
National Monitoring & Evaluation System	4.83	0	90
Funding Opportunities for Research	4.08	1	80
Cross-Sectoral Collaboration Policies	4.83	0	70
Big Data Analytics & Optimisation	4.33	1	90
Robotics and Automation	3.50	1	60
3D Printing	4.33	1	90
Blockchain Technology	3.67	1	70
Artificial Intelligence	4.17	1	100
Augmented & Virtual Reality	3.50	0.5	70
Employee Training Programmes	4.33	0.5	85
Align 4IR Adoption with the Organisation’s Overall Strategic Goals	4.83	0	90
Involve Key Stakeholders in the Strategic Planning for 4IR Technology Integration	4.83	0	90
Regularly Review and Update the Strategy for 4IR Technology Adoption	4.67	0.5	90
Deploy 4IR Technologies in Overall Production Processes and Daily Workflows	3.67	1	80
Promote a Culture of Continuous Improvement, Development and Innovation	3.83	0.5	80
Invest in Necessary Infrastructure and Systems.	4.83	0	90

Source: Research survey (2025).

Table 5. Results from Round 2 Delphi consensus.

	Mean	Interquartile Deviation	Cc
Cross-sector collaboration policies	4.00	0	85
Set-up of 4IR- WEF Nexus commission for skills assessment, monitoring, feedback and alignment	4.67	0.5	95
Curriculum realignment and revamping	4.92	0.5	90
Funding opportunities for research and pilot projects	4.00	0	85
Public–private partnerships	4.98	0.5	90
4IR-WEF Nexus alignment with the National Development Plan	4.92	0.5	90
Digital literacy	4.92	0.5	90
Artificial intelligence	4.65	0.5	90
Big data analytics and optimisation	4.92	0.5	90
Blockchain technology	4.02	0.5	85
Robotics and automation	4.92	0.5	90
Internet of Things	4.00	1	90
3D printing	4.69	0.5	80
Incorporate employee training programmes	4.33	0.5	85
Align 4IR adoption with the organisation’s overall strategic goals	4.67	0.5	95
Involve key stakeholders in the strategic planning for 4IR technology integration	4.54	1	80
Regularly review and update the strategy for 4IR technology adoption	4.00	0	90
Deploy 4IR technologies in overall production processes and daily workflows	4.33	0.5	85
Promote a culture of continuous improvement, development and innovation.	4.00	0	90
Invest in necessary infrastructure and systems	4.02	0.5	85

Source: Research survey (2025).

5.4. Final Validated Framework

Following the Delphi Round 2, where all the constructs of the modified framework achieved consensus, a modified framework was developed that focused on national policies, organisational culture and individual training, as seen in Figure 5. The national policies emphasised the need for cross-sector collaboration policies, the establishment of the 4IR-WEF commission, curriculum reform, increased funding for research and pilot projects, and public–private partnerships. Organisational culture has been re-ordered to the middle level and is the operational foundation for long-term technological integration. The organisational culture comprises continuous investment in employee training, aligning 4IR initiatives with strategic organisational goals, and involving stakeholders in decision-making processes. Organisational culture also included the need for regular review and revision of strategy for 4IR integration and the deployment of 4IR technologies across daily workflows, establishing a culture of continuous improvement, innovation and investment in infrastructure and systems to foster 4IR innovations in the WEF Nexus. The organisational culture level reveals that 4IR integration is not solely dependent on tools and technologies but is a function of systems and behaviour within WEF sector organisations. The last layer focused on individual training, which comprised founda-

tional competencies such as digital literacy and 4IR skills like artificial intelligence, big data analytics, blockchain, robotics, Internet of Things, and 3D printing. The individual-training level emphasises the need to equip the workforce with the necessary skills and plays a significant role in transforming the WEF Nexus. Implementing this multi-level framework reveals an integrated approach for 4IR-enabled solutions in the WEF Nexus. The modified framework introduces a macro-meso-micro-architecture that links national policy instruments, organisational operating conditions, and workforce competencies into a single implementation logic, rather than presenting the Nexus mainly as a coordination problem among sectors. The modified framework, in contrast to other existing frameworks, introduces an institutionalised skills governance function to assess needs, realign curricula, and sustain feedback loops, addressing a recurring gap in WEF initiatives where training and capability development are fragmented or assumed.

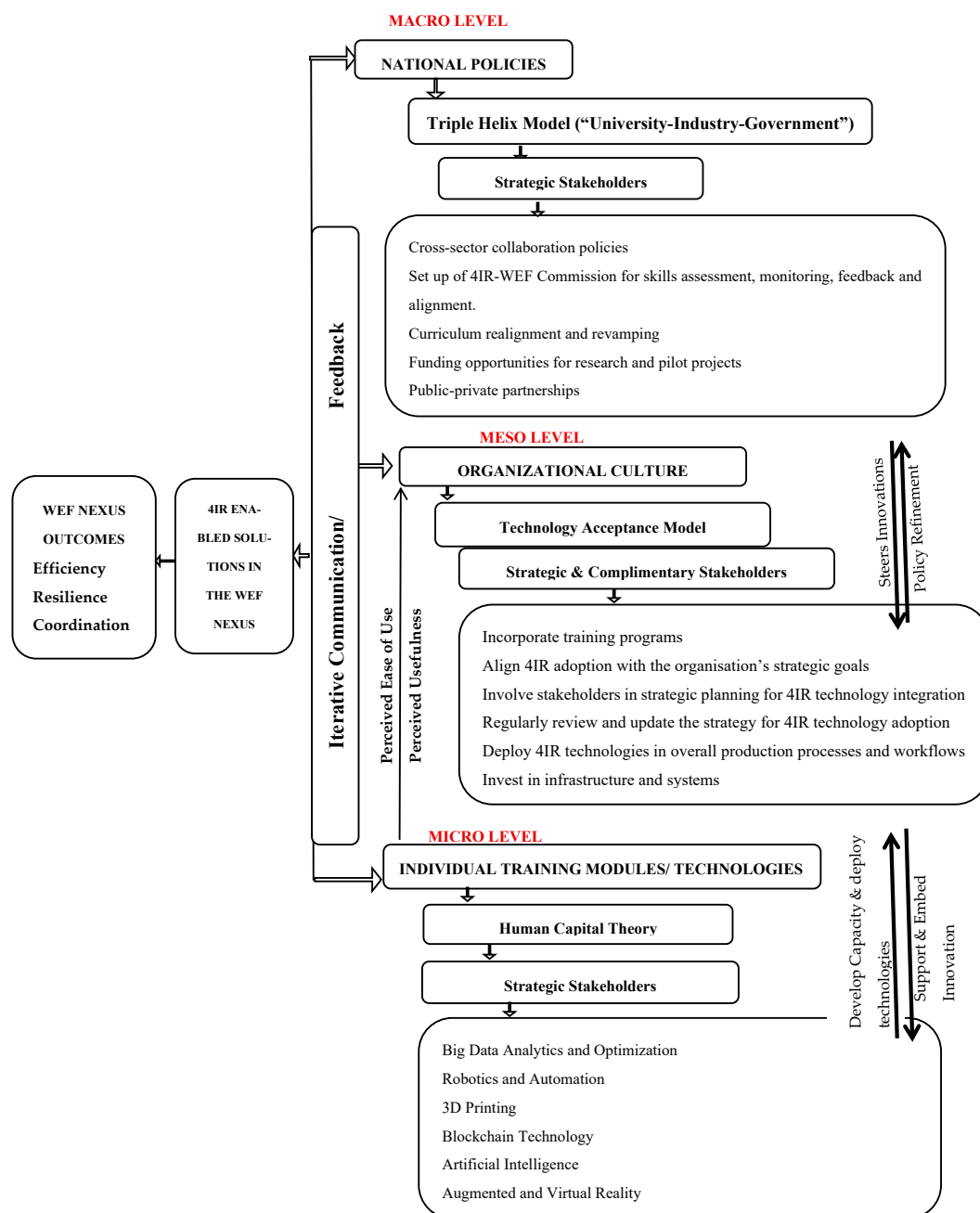


Figure 5. Modified framework for 4IR-enabled solutions within the WEF Nexus. Source: Research survey (2025).

6. Discussion

The modified framework developed in this study provides a comprehensive and concerted approach for integrating 4IR technologies within the WEF Nexus through the interconnected levels of national policies, organisational culture and individual training. In contrast to previous studies that have addressed the WEF Nexus and different 4IR technologies in a fragmented approach, this study holistically integrates the WEF Nexus and 4IR technologies. The segmentation of the framework into different levels emphasises the need for centralised and strategic approaches rather than disjointed and spontaneous efforts devoid of long-term sustainability. The findings of this study show that the integration of 4IR technologies into the WEF Nexus is contingent upon the synchronisation of human capital at national, organisational, and individual tiers. It re-emphasises that digital transformation in the WEF Nexus is a process that is influenced by interdependent capacity linkages rather than solely by the technology procurement. The results show that national policies, organisational culture, and individual competencies all work together to decide whether 4IR tools are successfully integrated into practice.

At the national policy level, the results revealed that fragmented governance, inadequate coordination, and obsolete curricula are fundamental to digital stagnation in the WEF sectors. Both survey respondents and experts pointed out that even the most advanced and impactful technology will fail without adequate enabling policies, curricula and funding strategies, or when these elements are misaligned. The study reinforces national policy as the strategic foundation of innovation capabilities rather than as a peripheral element. It emphasises that technological innovation across the WEF Nexus must include integrating education reform, 4IR skill development, and intersectoral collaboration, and calls for proactive national planning and policies for digital readiness, as opposed to it being a reactive element.

At the organisational culture level, the findings reveal that organisations with adaptive, learning-oriented cultures have the ability to achieve increased digital transformation and implement 4IR technologies across the Nexus. These organisational cultures also align with the assertion of Adebayo (2022) [65], who opined that an agile organisational environment plays a crucial role in technology adoption. The study reinforces the importance of leadership commitment, employee empowerment, and an environment that fosters experimentation as enablers of innovation. The respondents, however, pointed out that the SHRM principles may not apply to public-sector organisations, where HR practices are shaped by external regulations, funding, and other factors. The study recommends modifying the SHRM to account for systemic interdependencies, while acknowledging that collaboration and regulatory alignment are essential elements of human resource development and human capital accumulation in the public sector.

The individual-level training provides critical skills required by professionals within the Nexus to utilise 4IR technologies within the WEF Nexus effectively. The framework identifies skills such as artificial intelligence, big data, blockchain, robotics, and the internet of things as relevant 4IR skills. The framework also points out digital literacy as a foundational skill for technology integration. The need for professional training within the framework further establishes the importance of upskilling and reskilling human capital to foster innovations. It emphasises that national policies and organisational culture may fail without adequately trained personnel. It explains why technological solutions frequently fail to yield operational productivity and performance, as the deficiencies at any of these framework levels will weaken the coherence of the entire capability system. The development of this multi-level framework provides a strategic and structured approach to leverage 4IR technologies to build resilience and improve efficiency within the WEF Nexus. The elements of this framework, if properly implemented across all levels, can potentially

combat resource scarcity, inequality and sustainability challenges within the Nexus. The findings of this study reveal that individuals do not solely determine capabilities and skills but are also shaped by the structures in which they function, and position digital transformation as a multi-level alignment challenge, rather than a sequence of technical or training interventions.

This paper advocates for the development of system-embedded human capital (SEHC) and positions it as a necessary analytical construct for explaining system-level capability formation and alignment for 4IR-enabled transformation in complex public-sector institutions such as the WEF Nexus. SEHC builds upon and extends both HCT and SHRM by positioning human capital as an intrinsic property of a coordinated socio-technical system, rather than an isolated element located solely in individuals (HCT) or treated primarily as an organisational asset (SHRM). This study proposes SEHC as an emergent, system-level capability that arises when macro-level policy instruments, meso-level organisational learning conditions, and micro-level workforce competencies are coherently aligned such that 4IR technologies can be absorbed, deployed, routinised, scaled, and continuously improved within interdependent ecosystems such as the WEF Nexus. SEHC, therefore, treats “human capital for 4IR” not as an attribute of individuals alone, nor only as an organisational HR asset, but as a cross-level capability pipeline whose performance depends on the consistency of enabling policies, organisational routines, and deployable skills.

SEHC is specified through five tightly bound constructs. Policy Alignment (PA) captures the coherence and enforceability of national/sector instruments that enable 4IR uptake, such as standards and interoperability requirements, governance/commissioning structures, curriculum realignment, and funding mechanisms. Organisational Learning Culture and Change Readiness (OLC) captures the extent to which organisations support experimentation, learning routines, leadership commitment, resourcing, incentives, and workflow embedding of digital tools. Workforce Competency Stock (WCS) captures the distribution and depth of foundational digital literacy and advanced 4IR capabilities required for implementation. Cross-Level Coherence (CLC), which is the distinctive SEHC construct, is the degree of “fit” among PA, OLC, and WCS (i.e., whether policies enable organisational enactment, organisational routines make skills usable, and skills match role design and technical standards). Feedback Loop Strength (FLS) also captures the mechanism that maintains and recalibrates CLC over time through monitoring, skills assessment, iterative training/curriculum updates, organisational adjustments, and policy refinement. SEHC’s focal outcome is 4IR Integration Capability (IC), operationalised as sustained adoption beyond pilots, embedding into workflows, scaling across units, and maintenance over time.

The causal logic of SEHC is grounded in complementarity and weakest-link dynamics. Improvements at any single level (policy, culture, or skills) yield limited and unstable integration when the other levels remain misaligned, because the system’s integration capability is constrained by the most binding bottleneck. SEHC, therefore, predicts that durable 4IR integration results primarily from Cross-Level Coherence sustained by feedback loops, rather than from isolated investments in skills, technology, or policy in isolation. This study proposes that Cross-Level Coherence (CLC) is positively associated with 4IR Integration Capability (IC), such that systems with stronger alignment among Policy Alignment (PA), Organisational Learning Culture (OLC), and Workforce Competency Stock (WCS) demonstrate higher levels of routinised, scalable, and sustained 4IR integration than systems with weaker coherence. In comparison to other theories, like the dynamic capabilities, absorptive capacity and socio-technical systems theory, SEHC acknowledges the cross-level alignment mechanism that converts policy and learning into deployable

human capability in multi-actor ecosystems, particularly where no single organisation controls the enabling condition.

This study positions SEHC as a system-level capability where macro-level policy instruments, meso-level organisational culture, and micro-level workforce competencies are aligned through feedback loops for technology adoption to become routinised and scalable rather than episodic or pilot-bound. SEHC reveals that sustained innovation does not follow automatically from policy reform, organisational restructuring, or skills programmes implemented in isolation; rather, durable technological integration occurs when these elements are mutually reinforcing and linked by iterative communication and feedback across levels. This argument explains why well-intended reforms or policies can underperform because policy ambition may outpace organisational absorptive capacity, training may be delivered without enabling infrastructure, incentives, or standards, and organisational strategies may lack reinforcement from national education and partnership arrangements.

SEHC is different from already existing theories such as institutional theory and multi-level governance frameworks, not because it rejects their insights, but because it addresses a different explanatory bottleneck: how governance and institutions become usable, deployable capability. The institutional theory basically examines structural constraints, legitimacy, and how institutions regulate behaviour, according to (Balzano et al., 2025; Silva et al., 2024) [66,67], while multi-level governance clarifies cross-level interactions, coordination challenges, and jurisdictional complexity (Papadopoulos et al., 2025; Tamtik & Colorado, 2022) [68,69]. However, these two theories leave capacity weakly specified, and often treated as assumed, external, or a downstream outcome of governance arrangements. SEHC, therefore, extends existing theories as a capability-centred complement that specifies the missing mechanism linking policy intent, organisational enactment, and individual operationalisation. The core concept of the SEHC is to provide a diagnostic lens for identifying where and why transformation breaks down when initiatives remain fragmented.

A distinguishing feature of SEHC is that it explains system capability alignment for 4IR adoption, whether a system can absorb and routinise technology, whereas institutional theory foregrounds rules, legitimacy, and constraints, while multi-level governance foregrounds coordination across levels. SEHC also specifies a capability pipeline mechanism that recognises alignment of policy instruments, organisational culture, and competencies as the driver of outcomes. While institutional and governance frameworks often identify enabling or constraining conditions, they do not articulate how these conditions are converted into deployable human capital. SEHC particularly treats human capital as an emergent system property distributed across macro–meso–micro levels. Institutional theory commonly analyses organisational fields and institutional logics, while multi-level governance commonly analyses governance architectures and actor relations rather than the embeddedness of competence in routines and infrastructures. Another core characteristic of SEHC is that it enables pinpointing breakpoints such as skills without infrastructure and policy ambition without absorptive capacity or culture resistant to change, and therefore, it supports the sequencing of interventions. The existing theories often diagnose misfit or fragmentation but provide less granularity on which capability links failed and what to fix first. An understanding of SEHC explains why two systems with similar institutional arrangements or multi-level governance structures can experience different innovation outcomes because their embedded human capital alignment differs, which adds a discriminatory power beyond governance mapping alone.

SEHC, therefore, provides a holistic and integrated approach that advances human capital from micro-level interpretations of talent and skills to a macro–meso–micro capability alignment construct suited to interdependent public-sector ecosystems. It extends

HCT and SHRM by embedding human capital within coordinated systems characterised by mutual accountability and collaborative learning, and it complements institutional and multi-level governance frameworks by specifying how policy and governance arrangements translate into sustained technological integration. For the WEF Nexus, where 4IR adoption requires cross-sector coordination, organisational learning, and applied competencies, SEHC explains the historical failure of fragmented initiatives and provides a structured pathway for designing interventions that align policies, culture, and workforce skills into a coherent transformation map. It argues that individual 4IR competencies will predict integration outcomes more strongly when organisational learning culture and policy alignment are high, claiming that strength at one level cannot fully substitute for persistent weakness at another level, and that SEHC coherence will explain incremental variance in sustained integration beyond measures of dynamic capabilities and absorptive capacity, while policy effects on integration should be mediated by culture change and competency development.

The elements of this framework can also be scaled or adapted to several sectors, as it addresses the three levels of innovations and development, which have often been addressed in isolation. The framework solidifies the importance of systems thinking in tackling the complex challenges within the Nexus and driving sustainability and innovation. However, translating this framework into public-sector practice is neither linear nor frictionless. Public-sector WEF institutions operate under constraints that shape what is feasible, the pace of implementation, and the distribution of benefits. These constraints include procurement rigidity, fragmented mandates, audit and compliance requirements, short political or budgeting cycles, and limited discretionary spending for experimentation. Consequently, even where there is strong agreement on the importance of national policies, organisational culture, and individual competencies, implementation may still stall if enabling conditions such as predictable funding, interoperable data infrastructure, and stable interdepartmental coordination mechanisms are absent. This reveals that the framework should be interpreted as a capability alignment architecture rather than a guarantee of implementation success.

When implementing the framework, there should be a balance between central coordination and adaptive flexibility. The framework places national policy as a strategic anchor, but public-sector centralisation can also create bottlenecks when policy formulation, approvals, and budget allocations are slow or politically contested. In practice, the framework implies a hybrid governance logic: national policy should set interoperable standards, capability benchmarks, and accountability mechanisms, while allowing sector agencies and municipalities sufficient operational autonomy to pilot technologies, learn iteratively, and adapt solutions to local resource contexts. This trade-off is particularly salient in WEF systems where institutional responsibilities are distributed across multiple departments and tiers of government.

Another issue to consider in implementing the framework is sequencing and readiness gaps. Although the quantitative results and expert feedback support the prioritisation of policy-level enablers, policy instruments alone do not generate capabilities unless they translate into organisational routines and workforce development pathways. Conversely, training programmes introduced without enabling organisational conditions can result in trained incapacity, where staff have awareness but lack authority, infrastructure, or incentives to apply new skills. Similarly, investing in advanced 4IR tools without foundational data governance and digital literacy risks producing low utilisation, vendor dependency, and reputational damage when projects fail to deliver visible outcomes. The framework, therefore, implies that capability building should proceed through staged maturity, where foundational governance and data management capacity are strengthened

alongside targeted upskilling and organisational change, rather than assuming that one level can substitute for another.

The framework may also require public-sector WEF institutions to choose between investing in immediate service delivery needs (e.g., maintenance backlogs, staffing shortages, infrastructure failures) and allocating funds to innovation capacity (e.g., data platforms, pilot projects, training, change management). These trade-offs are amplified in resource-constrained settings, where the opportunity costs of digital transformation can be politically and socially sensitive. For this reason, the framework should not be read as prescribing uniform investment in all components simultaneously, but as supporting prioritisation decisions that reflect risk appetite, fiscal space, and system criticality. There are also socio-technical risks that accompany 4IR-enabled transformation in the WEF Nexus. These include data security and privacy risks, unequal access to digital tools across agencies and regions, and potential workforce resistance driven by concerns about surveillance, job displacement, or increased workload. If these concerns are not managed through transparent change governance, participation, and capability-sensitive job redesign, digital transformation may reinforce distrust and create implementation backlash. However, while these challenges may hinder the framework implementation, they can be overcome by stakeholder initiation meetings to seek the buy-in of all stakeholders and address the different stakeholders' concerns. The national government can also leverage international development financing to organise awareness campaigns and workshops for key officers and professionals within the WEF sectors. The government can also partner with developed countries for progressive curriculum comparison and revamping and upskilling programmes to initiate upskilling programmes and certifications. The framework is therefore best operationalised with explicit safeguards such as role-based training pathways, ethical and legal data governance, stakeholder engagement protocols, and mechanisms for organisational learning that treat early failures as informative rather than punitive.

Although the framework can be adapted beyond South Africa, applying it directly in other regions may be influenced by how stable their policies are, how government responsibilities are shared, whether centralised or decentralised, how strong public institutions and enforcement are, and how much trust and collaboration exist across sectors. The framework adoption may also be influenced by frequent political changes, weak coordination between ministries, limited funding, poor digital infrastructure, or low data governance capacity. However, this study proposes that the framework should be tailored to the realities of each region, rather than being applied as a one-size-fits-all model. The successful implementation of this multi-level framework can become a catalyst for transformative change in the WEF Nexus in South Africa and globally.

6.1. Practical Implications of Multi-Level Framework to Resource Governance and Innovations in Public-Sector Transformation

The multi-level framework developed in this study provides an approach to put innovation into action in public sector institutions, especially those involved in managing natural resources such as water, energy and food resources. The framework presents a clear, scalable, and systematic approach for incorporating 4IR technologies into these key service sectors. This framework can break down bureaucratic silos and fragmented governance structures that have historically hindered resource integration in South Africa. At the national level, the framework suggests creating a 4IR-WEF Commission, forming public-private partnerships, and reforming cross-sectoral curricula. These actions shift governments from being passive regulators to active enablers of innovation, promoting regulatory alignment and collaboration between institutions. The organisational culture layer changes public institutions into agile, tech-ready organisations through organised workforce training, investments in infrastructure, and the strategic alignment of innovation

goals. These actions challenge the traditional inflexibility of public administration and foster performance-based, mission-driven cultures that support ongoing innovation. For individual training, emphasis is placed on acquiring skills in AI, IoT, big data, and digital literacy. This ensures that public sector workers are not just following policies but are also co-creators of technological change. It redefines civil servants as strategic assets capable of engaging in and adjusting to rapid technological advancements.

This framework can serve as a governance innovation strategy that encourages vertical integration between broad policies and local capabilities, making it possible and sustainable to transform the public sector. It provides a model for low- and middle-income countries facing challenges with technological adoption, institutional resistance, and the need for sustainable resource management.

6.2. Implications for Policies on Workforce Reforms

The findings of this study show that effective workforce reform needs to go beyond occasional training or organisational changes. The proposed multi-level framework indicates that strategic, systemic, and synchronised reforms are crucial for developing a 4IR-ready workforce within the WEF Nexus. It points out that for sustainable resource management, efforts should be put into curriculum reform, upskilling and reskilling, and coordination among institutions. At the policy formulation level, which is the government level, the framework proposed revising educational curricula to include digital skills and sustainability. The framework specifically points out that realigning curricula and establishing a national feedback system are essential policies. This calls for a shift from reactive to proactive workforce development strategies, where skills planning matches emerging technology trends. At the organisational level, the study stresses the need for dynamic and ongoing learning systems. Workforce reforms should not only focus on compliance or performance management but also prioritise adaptive learning cultures, teamwork across departments, and stakeholder involvement. For instance, incorporating 4IR training into organisational strategies can help close the skill-innovation gap that affects resource-sector performance in South Africa. The framework also recommends making workforce transformation a priority through dedicated commissions, such as the 4IR-WEF Commission. Their mandate would include monitoring skill needs, ensuring policy consistency, and coordinating public-private learning partnerships. This approach will prevent fragmented reforms and support sustained skill development. The framework also implies that workforce reform policies must also consider inclusion and mobility between sectors, especially since digital divides continue to exist. This study makes a clear case for linking workforce strategies with national innovation and sustainability goals. The implication is that without intentional, policy-driven workforce transformation, even the best technological solutions may fail due to a lack of human capability and institutional readiness.

7. Conclusions and Recommendations

The findings of this study reveal that the integration of 4IR technologies in the WEF Nexus depends on the alignment of human capital across national, organisational and individual levels. The findings reveal that digital transformation is not totally shaped by the availability of technology, but by the coherence of the ecosystem in which the technology is embedded. The validated framework points out the need for a system-embedded human capital (SEHC) approach, which extends the HCT and SHRM. The findings reinforce that fragmented approaches, whether focused on tools, training or organisational reforms, cannot achieve sustained innovation. Instead, innovation should be seen as a multi-level alignment challenge that requires integrated and coordinated action across all levels. The validated framework provides a practical and theoretical pathway for strengthening digital

readiness and technology adoption in the WEF Nexus. Based on the findings of this study, the authors recommend that:

1. Policymakers should consider establishing a National 4IR–WEF Capability Council that will manage and oversee the revamping of curricula, set digital competency standards, and coordinate cross-sectoral implementation to ensure consistent skills pipelines. To operationalise the proposed National 4IR–WEF Capability Council, it should be formally established through a government mandate with a clear responsibility to coordinate 4IR capability development in the WEF sectors, set shared standards, align budgets, and monitor implementation. The council should be supported by a technical secretariat that runs day-to-day delivery and convenes time-bound working groups on (i) policy and standards (data governance, interoperability, regulation), (ii) organisational capability (procurement reform, change management, performance incentives), and (iii) skills pipelines (curriculum reform, certification, upskilling). Stakeholders should have defined roles with progress tracked through a national roadmap and annual capability scorecards.
2. WEF institutions should create innovation accountability agreements that will enable every organisation to include digital-learning targets, experimentation metrics, and leadership development benchmarks into their annual performance metrics or key performance indices.
3. Higher Education Institutes (HEIs) should develop rotational, cross-sector digital programmes to encourage skill development where engineers, data scientists, water managers, energy technicians, and agricultural specialists exchange roles for short periods to upskill and reskill.
4. There should be professional skill acquisition benchmarks and metrics to monitor and certify progression in 4IR competencies and allow workers to transfer verified capabilities across WEF sectors, reducing duplication and strengthening labour mobility.

8. Study Limitations and Suggestions for Further Studies

The major limitation of this study is that the proposed framework was validated through cross-sectional, perception-based evidence from PLS-SEM and Delphi consensus rather than empirically tested for operational outcomes from implemented 4IR projects in the WEF Nexus. This study acknowledges that this conceptual validation may limit measurable impacts and not fully capture implementation trade-offs or failures of the framework. This study suggests that future studies should explore quantitative validation and comparative designs by empirically testing the framework using pilot testing, measurement invariance testing, multi-group analysis, and longitudinal or panel designs. The Delphi panel composition may have also shaped the validated framework's prioritisation toward the energy sector, without adequate inclusion of water and food sectors. Future research should also model the framework as a dynamic, multi-level process in which policy alignment (macro), organisational learning culture (meso), and individual competencies (micro) co-evolve through reciprocal feedback loops over time rather than assuming contemporaneous, one-directional effects. Future studies can collect repeated measures of the three levels and estimate time-lagged and cross-lagged relationships to test whether changes in policy instruments precede culture change and competency development, and whether improvements in competencies subsequently reinforce organisational routines and inform policy recalibration. Further studies should also conduct comparative studies that benchmark this framework against other 4IR–WEF integration frameworks. Future studies should also explore cross-regional adoption comparisons within South Africa and cross-country comparisons between South Africa

and other Sub-Saharan African countries to assess the transferability and scalability of the framework.

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