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RESEARCH

A Machine Learning Climate Finance Framework for Environmental Pollution Credits among Smallholder Farmers in the Western Cape, South Africa

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ABSTRACT

BACKGROUND: The growing global population, expected to reach 9.7 billion by 2050, is increasing the demand for sustainable food system practices and resilient food systems. The food system contributes to nearly one-third of global emissions, while smallholder farmers, who survive on farming, face challenges related to climate change and inefficient resource use. Existing research suggests a lack of innovative approaches to reduce food system emissions and waste while improving sustainability in the face of climate change.

OBJECTIVES: The study's primary objective is to propose a conceptual climate finance framework to enable small-scale farmers to reduce pollution and generate verifiable environmental pollution credits. The study addresses a significant gap in the literature by proposing a machine learning-based conceptual climate finance framework for an environmental pollution credit system, aimed at small-scale farmers in the Western Cape, South Africa.

METHOD: The study adopted an organisational cybernetics systems approach to propose a conceptual climate finance framework. This framework will use machine learning (ML) techniques, such as supervised learning, that can accurately predict and classify new and previously unseen data, learning from labelled datasets collected from various datasets in food systems.

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FINDINGS: The study's findings suggest that the proposed climate finance framework will not only help optimise farm practices but also allow farmers to earn pollution credits, offering new revenue streams. The study supports the COP29 agenda and drives advancement towards the Sustainable Development Goals (SDGs). The proposed framework contributes to advancing the SDGs and driving meaningful environmental change in the region.

KEYWORDS: *Artificial Intelligence; Machine Learning; Climate Finance; Sustainable Development Goals; Organisational Cybernetics; Systems Approach.*

INTRODUCTION

The 2030 Agenda for Sustainable Development Goals (SDGs) views climate change as the biggest challenge of our time because of its negative impact on sustainable development (UN, 2020). SDG 13 focuses on seeking ways for resilience and capacity to adapt to climate change-related hazards and disasters. The pressure on food security and environmental sustainability has highlighted the need to transform food systems to increase food production and minimise environmental impact (Naicker *et al.*, 2025). The challenge of the current food systems is the ability to feed the growing population without increasing gas emissions and destroying the environment. This challenge to sustainable food systems requires a transformative change to farming practices. Most developing countries' economies depend heavily on agriculture for employment, income, and food security (FAO, 2022).

Several researchers concur that new technologies can potentially transform the food system at an exponential rate (Masekwana and Jokonya, 2025). Previous studies note that crop yields are expected to decline by more than 50% due to climate change, driving up food costs and affecting global GDP by 2100 (Masekwana and Jokonya, 2025). The irony is that while the food system is the most affected sector by the effects of climate change, it also contributes more than a fifth of all global gas emissions, causing a negative impact on climate change. The literature suggests the existence of an unequal distribution of global climate finance, with small-scale farmers remaining under-served, despite them bearing the harsh realities of climate change in the form of soil degradation, declining crop yields, and food insecurity. The portion of global climate finance reaching small-scale farmers is only 1.7% (FAO, 2022).

BACKGROUND CONTEXT

The South African economy heavily depends on the growth of the food sector to create jobs and reduce unemployment. With a population of about 60 million, South Africa has about 4 million small-scale farmers and 36,000 commercial farmers (Aroba and

Rudolph, 2024). Previous studies noted that food production is a major contributor to environmental degradation and a cause of climate change with one-quarter of global gas emissions attributed to the food systems (Aroba and Rudolph, 2024). In the case of South Africa, about 20% of gas emissions come from the food systems. Whilst there is no clear path to solve gas emissions from the food systems, digital technologies present opportunities to reduce the amount of global gas emissions as part of sustainable food systems (Aminetzah *et al.*, 2022). The advancement in technologies has brought opportunities for innovation to reduce gas emissions in food systems, mitigating the impact of climate change.

Food System and Climate Change

SDG 13 calls for urgent measures to address the challenges associated with the threat of climate change. Studies suggest that crop yields are predicted to decline by between 10% and 50% by 2030 due to the effects of climate change (Ozor *et al.*, 2025). Ironically, the food system (Figure 1), severely impacted by climate change, is a main contributor to greenhouse gas emissions (GHG), 25% of global gas emissions annually (Ozor *et al.*, 2025). Previous studies suggest that the negative effects of climate change on food systems, such as drought, crop pests, diseases, and pollution, exacerbate small-scale farmers' poverty, nutrition insecurity, and food insecurity (Tchonkouang *et al.*, 2024).

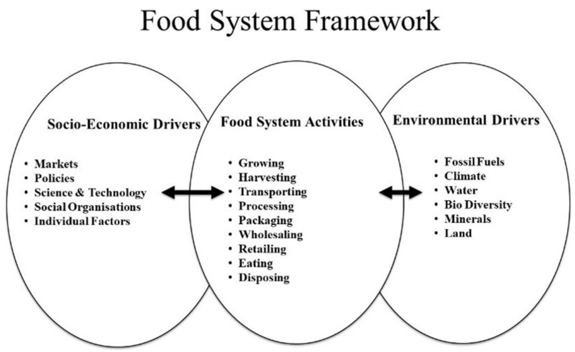

Figure 1: Food Systems Framework
Source: Constructed by Authors

Climate change not only affects food availability in developing countries but also reduces food nutrients such as zinc, iron, and proteins in staple crops, thereby decreasing their nutritional value (Von Braun *et al.*, 2021). In addition, the high temperatures associated with climate change affect the soil's organic matter structure, thereby reducing nutrients and water-retaining capacity of the soil. This is happening at a time when the global population is growing faster, with an expected growth of 33% in 30 years; this will require an increase of 60% in food production to feed the growing population (Soares *et al.*, 2019). The challenge of climate change effects on food security is that approximately 60% of global food output is still dependent on rain-fed water production, making the food system vulnerable to rainfall patterns (FAO, n.d.).

The irony of the reality of climate change is that developing countries are the most impacted whilst they contribute least to gas emissions. In addition, they have the largest cases of poverty and food insecurity, with their livelihood heavily dependent on agriculture. Several researchers have acknowledged the negative impact of climate change on small-scale farmers' food security and sustainability (Ogundeji, 2022). Climate change has harmed most small-scale farmers' livelihoods and food security, mostly in the global South. Several researchers concur that climate change remains the biggest threat to economic development in the global South as it affects food production, causing food insecurity (Ogundeji, 2022). The unpredictable high temperatures and low rainfall have had a serious negative impact on the sustainable food system in the global South (Figure 2). Climate change has caused a decrease in crop yields, resulting in low income and food insecurity in small-scale farmers (Ogundeji, 2022).

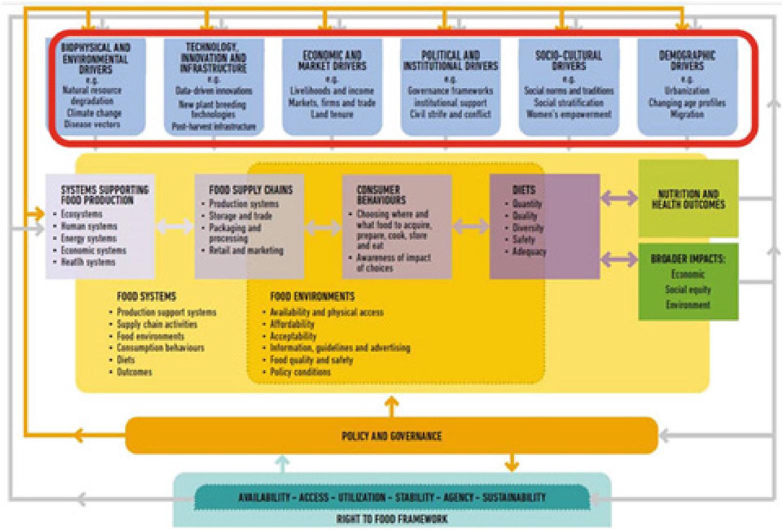

Figure 2: Conceptual framework of sustainable food systems
Source: Neufeld *et al.*, 2023

In most developing countries, where approximately 70% of the population is dependent on agriculture, there is a strong link between the sustainability of agriculture, income, employment, and food security (Ogundeji, 2022; Neufeld *et al.*, 2023). The small-scale farmers who rely mostly on rainfall for food production are in great danger from the negative effects of climate change. Most developing countries are water-scarce, making it difficult for small-scale farmers to rely on sources other than rainwater, resulting in a reduction in food production and contributing to the challenge of food insecurity (Ogundeji, 2022). Therefore, this study focuses on mitigating environmental pollution in sustainable food systems.

Climate Finance for Sustainable Food Systems

The Paris Agreement encourages all nations to fight together to reduce gas emissions and strengthen their capacity for resilience to respond to climate change effects through adequate support (Gomez-Echeverri, 2018). The 2015 Paris Conference Agreement agreed to mobilise US$100 billion in climate change finance by 2025; this finance is to help the mitigation of and adaptation to the severe effects of climate change. COP29 pledged to reduce gas emissions by 43% by 2030. This significant reduction in gas emissions is a huge undertaking that requires massive investment; wealthy countries should lead in providing financial assistance through a climate finance framework (UNFCCC, 2024). COP29 defined climate finance as the allocation of financial resources towards mitigation and adaptation of the negative effects of climate change and the reduction of gas emissions and adaptation to the challenges posed by climate change. It further defined climate adaptation as the preparedness efforts to deal with the consequences of climate change, such as droughts and floods.

The COP29 climate summit (finance COP) reached a consensus on climate finance related to carbon markets, calling for more transparency and efficiency of voluntary carbon trading systems worldwide. The issue of transparency is key to the success of climate finance. Climate change shocks are expected to put many households in developing countries into extreme poverty by 2050 (UNFCCC, 2024). Against this background, one of the COP29 priorities was a call for action on reducing the impact of climate change on people's lives, livelihoods, and nature. More action is required to reduce the impact of climate change in causing hunger and malnutrition through investing in solutions that enable vulnerable small-scale farmers to adapt to the climate crisis (UNFCCC, 2024).

Digital Transformation of the Food System

Tsan *et al.* (2019) defined the digitalisation of food systems as the application of digital technologies to the whole range of food system value chains to overcome food insecurity and climate change adaptation challenges. Digital technologies have the potential to reduce high input costs and promote production efficiency, reducing gas emissions, thus resulting in sustainable food systems; these are some of the challenges faced by small-scale farmers in developing countries (Doukas *et al.*, 2024). Previous studies suggest that digital technologies have helped address issues of climate variability, food insecurity, and environmental degradation (Mudzielwana, 2025). This has witnessed improved productivity and the ability to adapt to the harsh realities of climate change, ensuring higher food security and sustainability (Masekwana and Jokonya, 2025). Previous research noted an increase in digital technology adoption in food systems: in Africa, 13% of small-scale farmers have access to technologies, helping them to address challenges in the food systems (Ozor *et al.*, 2025).

Several researchers have highlighted the need for digital transformation of food systems to overcome severe disruption forces such as climate change and the increased food demand associated with world population growth (FAO, 2022). The world population is expected to reach 9.7 billion by 2050; increasing food demand puts pressure on water, arable land, and the environment, causing climate change (FAO, 2022). On that note, it is therefore important for food systems to embrace emerging technologies in mitigating climate change to achieve sustainable food production (FAO, 2022). The application of big data technologies such as artificial intelligence (AI) and sensors reduces food waste in the food system, which is also one of the major contributors to gas emissions (Joubert and Jokonya, 2021; FAO, 2022).

Artificial Intelligence and Machine Learning Food Systems

The application of emerging technologies such as AI (Figure 3) has the potential to reduce food waste through the food system. The reduction of food waste contributes to achieving sustainable food systems that face challenges due to high food demand, which puts pressure on the environment (Senoo *et al.*, 2023). AI and robotics have been at the forefront in helping reduce food waste in the food system. AI algorithms have been used to reduce food waste in the food systems through demand forecast, tracking food expiry dates and sorting produce for the market. AI's ability to focus on food demand is important for efficient and effective food systems that curb overproduction, overstocking, and waste (Joubert and Jokonya, 2021). Small-scale farmers, considered the backbone of sustainable food systems in developing countries, need to embrace digital technologies in the fight against climate change.

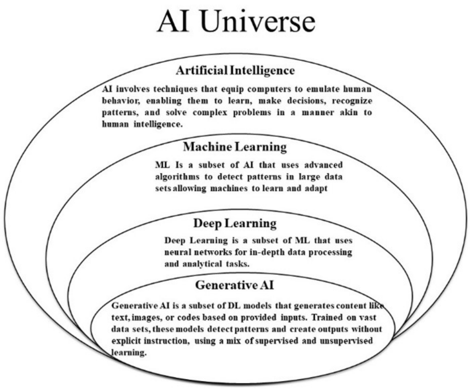

Figure 3: AI Universe
Source: Constructed by authors

Emerging technologies such as AI and the Internet of Things (IoT) have emerged with promising solutions through facilitating the optimisation of resource usage, enhancing monitoring, and facilitating data-driven decision-making to promote sustainable food systems (Joubert and Jokonya, 2021). Innovative technologies have been credited with maximising yields and optimising resource utilisation through integrating cyber-physical devices and systems. The holistic integration of technologies has brought benefits to the management of various resources in the sustainable systems ecosystem, such as energy, water, pesticides, weedicides, and fertilisers among others, (Kumar *et al.*, 2022; Neufeld *et al.*, 2023)

Machine Learning in Sustainable Food Systems

Previous studies highlighted that the application of machine learning (ML) has transformed food systems through capabilities such as yield prediction, disease prediction and pest control, quality prediction, and enhanced sustainability in the food system (Senoo *et al.*, 2023). Many researchers have proposed ML data-driven approaches to offer potential solutions to these growing complex challenges (Senoo *et al.*, 2023; Doukas *et al.*, 2024). ML's ability to process large datasets and computational power has given hope of providing the solution to some of the complex challenges of climate change. Machine learning methods, such as supervised learning, can potentially transform food systems faced with unprecedented challenges of climate change (Senoo *et al.*, 2023).

The recent technological advancement has seen several ranges of ML techniques greatly improving models through specialisation and increased efficiency (Senoo *et al.*, 2023). Some notable examples of ML include supervised learning (that can accurately predict and classify new and previously unseen data learning from labelled datasets), reinforcement learning (where an agent can update their knowledge continuously without the need for periodic retraining), reinforcement learning with human feedback (the agents can adapt and improve through human feedback) and lastly transfer learning (takes the pre-trained model and adapts it to the new related problems) (Senoo *et al.*, 2023). Based on the advancement in ML techniques, there is an opportunity for the technologies to have an impact on climate change through a framework of climate finance (COP28). The ability supports SDG innovation for development through the automation of tasks to bring efficiency in sustainable food systems (Senoo *et al.*, 2023)

METHODOLOGY

Figure 4 presents the connection between the problem context and systems approaches, and the problem context in food systems. The systems approach provides a useful framework to identify the primary focus of each approach and the types of problems to which they are most suited. Reynolds and Holwell (2010) highlight the alignment of system approaches with specific problem contexts. Based on that, any given problem context can be meaningfully matched to a corresponding (dominant) systems approach. Figure 4, therefore, reflects the degree of inter-relatedness and interdependencies, while the unitary, pluralist, and coercive axes represent the levels of engagement with multiple perspectives.

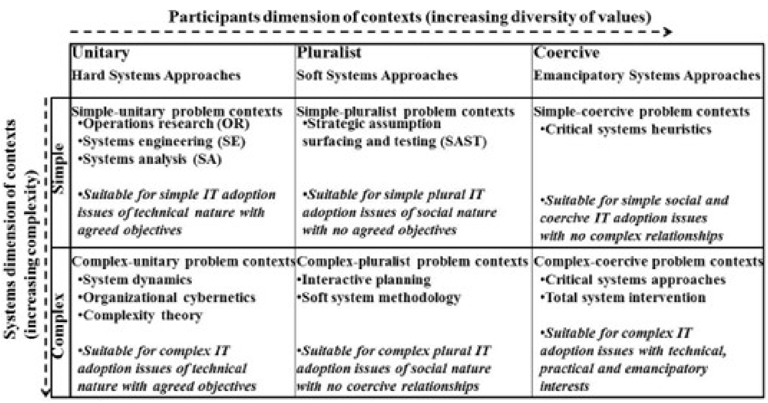

Figure 4: Relationship between Systems Approaches and Climate Finance Context

Source: Adapted from Jokonya, 2014

Figure 4 suggests that hard systems thinking approaches are for climate change food systems that are simple, and complex problem situations in food systems. Situations with clear objectives are more aligned with hard systems thinking (Ulrich and Reynolds, 2010; Jokonya, 2017). The shortcomings of hard systems thinking are in handling complex, pluralistic problem situations; it tends to oversimplify the social perspectives involved. In contrast, subjective food systems problem situations are aligned with soft systems thinking approaches, which accommodate multiple stakeholder perspectives (Ulrich and Reynolds, 2010; Jokonya, 2017). The weakness of soft systems thinking is dealing with conflicts and coercive relationships. The coercive and conflict issues in climate finance within food systems are aligned with emancipatory systems thinking approaches as it facilitates democratic debate around issues, as depicted in Figure 4 (Ulrich and Reynolds, 2010; Jokonya, 2016a). Lastly, complex climate finance problem contexts that involve technical, social, and emancipatory concerns in food systems are more aligned with critical systems thinking (Jackson, 2010; Jokonya, 2016b).

In summary, the systems approach helped to map the climate finance problem context decision-making in food systems. The climate finance problem context is more aligned with the complex unitary context of the hard systems. Based on the reviewed literature, there is consensus on the challenges of climate change to humanity and the need for action. Since there is consensus on the challenges of climate change and funding, the problem is how to operationalise climate finance to achieve the intended goals for food systems sustainability. Organisational cybernetics of hard systems, which aligns with the complex system, will be used to analyse the problem context.

Organisational Cybernetics

Organisational cybernetics is an interdisciplinary science applied to management; it criticises the limitations of traditional organisational hierarchical structures for not being suitable for modern organisations (Beer, 2004). The organisational cybernetics' viable systems model (VSM) has been recognised for its ability to guide and provide insights into social systems (Jokonya, 2016b). Through decentralisation and structural changes, the VSM promotes a shared understanding of the problem context, empowerment, and autonomy of different parts of the system. In the case of food systems, the VSM promotes decentralised decision-making across various leadership levels, making it a valuable tool for diagnosing organisational structures and processes (Jokonya, 2014). Based on its structuralist epistemology, the VSM is designed to create adaptive and goal-seeking entities suitable for the food systems ecosystem.

As shown in Figure 5, the VSM consists of five key elements: System 1 (Implementation), System 2 (Co-ordination), System 3 (Operational Control), System 4 (Development), and System 5 (Policy). These elements must function effectively to maintain the viability of the overall system. Figure 5, System 1 (Implementation) shows the various components that perform tasks to achieve the system's purpose. System 1 responds to environmental changes based on its priorities and is self-sustaining. The system objectives and goals for climate change finance are set by System 5, translated into targets, and performance is reported back to System 3. System 2 is responsible for co-ordination and auditing, ensuring that climate change finance rules and regulations are followed. System 3* within System 3 oversees auditing to ensure targets (System 3), rules, and regulations (System 2) are met. System 3 manages operational control, involving performance monitoring and maintenance of the climate change finance food system.

System 4 is responsible for handling development and decision-making based on data from System 3 and changes in the external food systems environment. It helps predict the future state of the food system based on internal and external information. System 3 receives information for immediate interventions, and System 5 receives information for long-term planning. Additionally, System 4 is involved in research, development, and corporate planning. System 5 ensures the implementation of policies by System 3 and formulates policies using information from System 4. System 5 ensures its adaptation to the environment for survival and balances external and internal demands on the organisation.

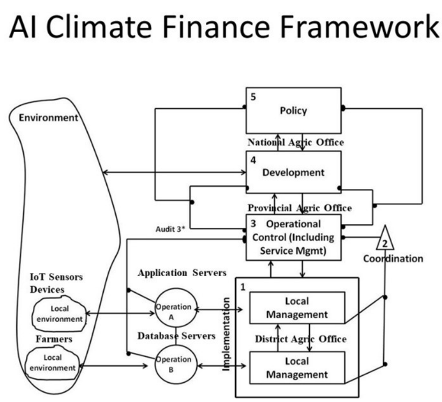

Figure 5: The AI Climate Finance Viable System Model
Source: Adapted from Jokonya, 2014

This section highlighted how the viable systems model can support the design of the proposed AI climate finance framework for food systems. It also demonstrated the alignment between food systems' climate change challenges and the VSM from a systems approach perspective. The next section explores how AI can enhance climate finance in food systems.

Machine Learning Climate Finance Application

Machine learning (ML) will handle large datasets to learn from data, adapt over time, and be efficient in food systems resource usage. ML learning methods such as reinforcement learning or transfer learning, can adapt to new environments and make informed decisions. These ML capabilities are important in developing a framework for climate change finance for sustainable food systems. ML can use natural language processing and the generation of images, text, video, and audio, paving the way for different applications of the food systems. ML's ability to process large datasets and computational power has given hope of providing the solution to some of the complex challenges of climate change. The use of ML methods, such as supervised learning, has the potential to transform food systems.

The climate finance framework will use ML techniques such as supervised learning, which can accurately predict and classify new and previously unseen data, learning from labelled datasets collected from various sources at System 3. Reinforcement learning updates knowledge continuously without the need for periodic retraining in System 4. Reinforcement learning with human feedback will adapt and improve the food systems process through human feedback, and lastly, transfer learning will take the pre-trained model and adjust it to the new food systems-related problems. The AI conceptual climate finance framework provides data-driven evidence from the food system ecosystem on the impact of climate change. The conceptual framework provides quick responses and a larger-scale sustainable food system improvement. The conceptual framework supports SDG 13 innovation for development through automation of tasks to bring efficiency to sustainable food systems.

DISCUSSION

While researchers have acknowledged the potential benefits of AI in sustainable food systems, not many studies have focused on the application of AI to climate finance in food systems. There is a notable gap in the literature regarding how an AI climate finance framework can assist in mitigating the impact of food production on climate change from a climate finance perspective. Several researchers agree that interventions are needed to promote sustainable food production in the food system. Therefore, this study proposes an AI framework for climate change mitigation based on climate finance. The study contributes to the understanding of AI applications on climate change finance for sustainable food systems. It addresses the research gap in proposing an AI conceptual climate finance framework to facilitate climate change mitigation by small-scale farmers in developing countries. The literature suggests the existence of an unequal distribution of global climate finance, with small-scale farmers remaining under-served despite them bearing the harsh realities of climate change in the form of soil degradation, declining crop yields, and food insecurity.

An AI conceptual climate finance framework for food systems improves resource usage, such as fertiliser, irrigation water, and pesticides, resulting in reduced environmental pollution in the food systems. The verifiable information from the ML application will make the climate payment process quicker and more transparent. The IoT sensor devices installed at different positions in the field will collect data on various activities that are part of the food systems matrix developed in consultation with stakeholders. Agriculture district offices will have the autonomy to collect and analyse data for climate finance based on thresholds agreed by stakeholders. A cloud-based application collects data from small-scale farmers who are paid based on their food systems practices. With food systems being one of the biggest polluters of the environment, every effort to address the problem of climate change associated with the food system is worthwhile.

CONCLUSIONS

The literature acknowledges that climate change is the biggest challenge to humanity because of its negative impact on sustainable development (UN, 2020). SDG 13 focuses on seeking ways for resilience and capacity to adapt to climate change-related hazards and disasters. The pressure on food security and environmental sustainability has highlighted the need to transform the food systems to increase food production and minimise environmental impact. The study proposed an AI climate finance framework for mitigating climate change's impact on food systems. Several researchers agree that interventions are needed to promote sustainable food production in the food system. The study contributes to the understanding of AI applications in climate change finance for sustainable food systems. This study addresses the research gap by proposing an AI conceptual climate finance framework to facilitate climate change mitigation by small-scale farmers in developing countries.

This study adopted a systems approach to map the climate finance problem contexts and decision-making in food systems. The climate finance problem context is more aligned with the complex unitary context of the hard systems. Based on the reviewed literature, there is consensus on the challenges of climate change to humanity and the need for action. Since there is consensus on the challenges of climate change and funding, the problem is how to operationalise climate finance to achieve the intended goals for food systems sustainability. Organisational cybernetics of hard systems, which aligns with the complex systems, will be used to analyse the food systems problem context. The proposed conceptual climate finance framework for an environmental pollution credit presents an innovative and scalable solution to the pressing challenges faced by small-scale farmers in the Western Cape.

The ability to generate pollution credits creates new revenue streams for smallholder farmers. The proposed conceptual framework will encourage sustainable practices, making farmers more resilient to the impact of climate change. Linking smallholder farmers to international climate finance markets can enhance their global competitiveness. The conceptual framework will enable farmers to optimise resource use, improve sustainability, and participate in global climate finance markets, supporting the COP29 agenda. With the right support, the proposed framework could significantly contribute to advancing the Sustainable Development Goals (SDGs) and drive meaningful environmental change in the region. Despite the mentioned contribution, there are limitations worth noting. The proposed conceptual framework has not yet been evaluated, which is part of the next phase.

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Professor Osden Jokonya is an academic in the Department of Information Systems at the University of the Western Cape in South Africa. Before joining academia, he spent more than 20 years in the IT industry. He held senior IT positions in various sectors, including mining, retail, manufacturing, financial services, insurance, utility, education, and other sectors. He has presented several papers at international conferences in Africa, Europe, Asia, and America, in addition to publishing several papers. Professor Jokonya sits on several local and international Association of Information Systems committees. His current research focus is on the adoption of emerging technologies (Social media, Mobility, Big Data Analytics, Financial Technologies, Blockchain, Drones, AI, and Cloud Computing) in food systems.

Professor Dr Ing. Oliver Moravčík is a distinguished Slovak academic, researcher, and university leader with over four decades of expertise in automation technology, applied informatics, and digital systems. He is the former Rector of the Slovak University of Technology in Bratislava (STU) and has held several senior leadership roles, including Vice-Rector for Strategic Projects and Development, Director of the Advanced Technologies Research Institute, and Dean and Vice-Dean of the Faculty of Materials Science and Technology in Trnava. Professor Moravčík holds advanced degrees in Automation Technology and Process Computational Technology from Technische Hochschule Ilmenau, Germany, where he also completed his PhD. He has played a key leadership role in several major international and EU-funded research and development projects totalling over €90 million. His contributions to higher education and science have earned him prestigious honours. Professor Moravčík is also a prolific author, with 49 publications indexed in Scopus and 43 in Web of Science.

