PAPER • **OPEN ACCESS**

Digital and circular technologies for climate-smart and sustainable agriculture: the case of Vietnamese coffee

Digital and circular technologies for climate-smart and sustainable agriculture: the case of Vietnamese coffee

Van Duy Nguyen[1,2*], Tri Cong Pham[3], Thu Thuy Pham[1], Anh N. Phan[2]

[1]Institute of Biotechnology and Environment, Nha Trang University, Khanh Hoa, Vietnam
[2]School of Engineering, Newcastle University, Newcastle upon Tyne, United Kingdom
[3]School of Computer Science and Engineering, Thuy Loi University, Hanoi, Vietnam
*Corresponding author, E-mail: duynv@ntu.edu.vn; duy.nguyen@newcastle.ac.uk

Abstract. This comprehensive article addresses the pressing challenges confronting the global agriculture, primarily driven by climate change and resource constraints. With a focus on promoting climate-smart and sustainable agricultural practices, the study explores the transformative potential of emerging technologies, e.g., the innovative use of digital technologies like Internet of Things, Artificial Intelligence, and Blockchain, showcasing real-world examples of their benefits, and circular technologies, e.g., waste-to-value practices. The challenges of population growth, climate change, environmental impact, and the plight of smallholder farmers are elucidated. Climate-Smart Agriculture initiatives supported by the World Bank Group demonstrate practical efforts in addressing these challenges, aligning with sustainable development goals. Here, we introduce an innovative and smart agriculture (INNSA) platform for the creation and operation of sustainable coffee value chain in Vietnam as a case of study. Thought-provoking questions for future research conclude the review, encouraging interdisciplinary collaboration. In summary, this article provides a compelling case for adopting sustainable agricultural practices through digital and circular technologies, offering a roadmap for global agriculture's transformation and resilience in the face of climate change.

1. Introduction

Agriculture has played a vital role in human civilisation, but today, it faces unprecedented challenges due to climate change and resource constraints. Climate-Smart Agriculture (CSA) is an approach to farming and land management that aims to address the challenges posed by climate change while ensuring sustainable agricultural production, food security, and the well-being of farmers and rural communities. Therefore, promoting climate-smart and sustainable agriculture is urgently needed. In this comprehensive review, we delve into the innovative approach of employing digital and circular technologies to address these pressing challenges. By highlighting their potential, providing examples, and analysing their impacts, we aim to shed light on how these technologies can transform agriculture.

Here, we present here a case study from our current research that endeavours to establish an Innovative and Smart Agriculture (INNSA) platform tailored for the cultivation and management of a sustainable coffee value chain. The primary emphasis is on elevating the quality and augmenting the value of critical components within coffee supply chain in Vietnam, and then can be applied in other countries. This platform is meticulously created and developed, drawing upon the fundamental principles of pivotal digital transformation and smart agriculture technologies, including Smart Devices and Internet of Things (IoT), Big Data, Artificial Intelligence (AI), Blockchain, Source Traceability

Technologies, and Sustainable Design and Manufacturing to transform agricultural practices, enhance sustainability, and meet the demands of a rapidly changing agricultural landscape [1, 2].

2. Challenges of global agriculture and coffee farming in Vietnam

The global agriculture is facing the significant challenges in the coming decades:

1. Population growth: The world's population is projected to reach around 10 billion by 2050 [3], necessitating an increase in food production by up to 98% to feed this growing population.

2. Climate change: Agriculture is increasingly threatened by climate change, including erratic rainfall patterns, frequent floods, and droughts. Current agricultural practices also contribute significantly to greenhouse gas emissions, exacerbating climate change.

3. Environmental impact: Agriculture consumes vast quantities of natural resources, particularly fresh water, which is depleting rapidly. Expanding agricultural land would lead to further deforestation, causing environmental harm.

4. Smallholder farmers: Approximately 84% of the world's farmers are smallholders who produce a significant portion of the world's food [4]. However, they face challenges such as low productivity, inefficiency, and the adverse effects of climate change.

Therefore, it is worthy to emphasize the need for sustainable agriculture, encompassing environmental, economic, and social aspects, achieved through the application of technology, digitalisation, and innovation. Addressing these challenges is crucial to ensure food security for future generations.

Among these challenges, climate change has emerged as one of the gravest threats to agriculture, directly affecting food security, sustainability, and the livelihoods of millions in developing countries. Rising temperatures, erratic weather patterns, and resource scarcity have left crops vulnerable, and livestock exposed to health risks. Moreover, unsustainable farming practices, combined with the generation of vast amounts of agricultural waste, contribute to environmental degradation.

Traditional farming methods have proven inadequate in adapting to these multifaceted challenges. To address these issues effectively, we must tackle the following issues:

- Resilience: Farmers must quickly adapt to climate change, characterised by unpredictable weather patterns and extreme events like droughts and floods. CSA is imperative to ensure crop viability and food security.
- Resource efficiency: Agriculture is a major consumer of water, energy resources, fertilisers, chemicals, and pesticides. Efficient resource utilisation is crucial for sustainability.
- Environmental impact: Conventional farming practices often lead to deforestation, soil degradation, and excessive use of agrochemicals. Sustainable practices are essential for preserving ecosystems and biodiversity [5].

Vietnam is currently one of the world's top coffee producers and exporters, but this thriving industry faces a multitude of challenges: (1) *Climate impact*: Climate change has caused storms, droughts, and shifting rainfall since 2007, leading to a potential 50% loss in Robusta coffee production by 2050; (2) *Aging trees*: About half of Vietnam's coffee trees are 10-15 years old, risking lower quality and productivity; (3) *Unsuitable land use*: Recent expansion onto unsuitable land results in low productivity and high costs; (4) *Excessive inputs*: Past intensive farming practices led to excessive input use of fertilisers, pesticides and irrigation, depleting soil and inviting future problems; (5) *Fragmented production*: Small, scattered farms lead to unstable, low-quality production with a lack of processing facilities; (6) *Harvesting practices*: Widespread unripe and overripe cherry harvesting impacts coffee quality; (7) *Robusta dominance*: Vietnam primarily grows lower-priced Robusta beans; and (8) *Underused sustainable technology*: Smart and circular agriculture solutions are underutilised in Vietnam's coffee supply chain [1].

Compared to other ASEAN's leading coffee producers such as Indonesia and Laos, Vietnam faces a shared challenge in ensuring sustainability. However, each country has its unique set of challenges. Vietnam grapples with the scale of production, Indonesia with its diverse geography, and Laos with infrastructural limitations. Tailored solutions are essential to effectively address these specific coffee production challenges. It is crucial to tackle these issues to ensure the long-term sustainability and competitiveness of not only Vietnamese coffee but also the broader regional agriculture sector.

3. Innovative approaches to address challenges in agriculture

It has been suggested that digital and circular technologies can offer innovative solutions to the challenges mentioned above. This is because that they empower farmers with data-driven insights, enhance resource efficiency, promote sustainability, and offer economic benefits. They are essential tools for addressing the complex challenges facing agriculture in the modern world while contributing to food security and environmental stewardship. The followings are key approaches to address the challenges in agriculture.

3.1. Digital technologies for precision agriculture

Digital tools, such as the IoT, AI, and Blockchain, provide a data-driven approach to agriculture. These technologies offer concrete benefits:

- Weather monitoring: Real-time weather data allows farmers to make informed decisions. For instance, in Indonesia, farmers equipped with IoT weather stations can receive weather forecasts and optimise planting times accordingly.
- Precision irrigation: IoT-based systems provide precise control over water usage, reducing waste. In Thailand, smart irrigation systems have led to significant water savings while maintaining crop yields.
- Pest management: AI algorithms can predict and manage pest outbreaks, minimising the need for chemical pesticides. In Vietnam, AI-powered pest prediction models have helped reduce pesticide use by 30% while preserving crop quality.
- Data-driven farming: Analytics tools help farmers optimise resource allocation and crop selection. In Laos, data analytics have enabled farmers to tailor their planting decisions based on market demand, reducing post-harvest losses [6].

3.1.1. Digital technologies for climate change and COP26: The UN COP26 2021 conference on climate change emphasized the vital role of technology in addressing climate change challenges. Technology plays a significant part in both monitoring potential solutions and implementing climate change solutions. However, there is also a growing recognition of the environmental impact of e-waste generated by digital technologies. Responsible digitalisation is essential to address this issue and transition to a more climate-friendly society. Decision makers are urged to consider this key choice as technology is increasingly used to achieve net-zero emissions by 2050 [7].

3.1.2. Digital agriculture in addressing climate change and food security: Over the past three decades, advancements in automation, data processing software, web-based applications, and mobile tools have transformed farming practices with the goal of increasing efficiency in resource utilisation. Prior to 2010, agricultural monitoring relied on technologies like GPS, ground-based sensors, satellite maps, and data loggers. However, the emergence of Unmanned Aerial Vehicles (UAVs), low-powered wireless sensors, IoT devices, and robotics marked a shift towards Digital Agriculture (DA) and smart farming, enhancing economic development and sustainability in food production [8].

The transformative impact of DA has been increasingly recognised in addressing climate change and ensuring food security. Over the last three decades, advancements in technology, including automation, data processing software, mobile tools, and IoT devices, have revolutionised farming practices. The emergence of drones, robotics, and real-time monitoring systems marked the transition to DA, aimed at enhancing resource utilisation and sustainability.

DA encompasses a broad range of technologies, such as robotics, drones, IoT, and mobile applications, facilitating real-time monitoring of soil conditions, water resources, and weather patterns. This data-driven approach improves field productivity and reduces operational costs, benefiting both farmers and the environment. It also offers solutions to reduce greenhouse gas emissions, lower energy consumption, and minimise CO2 emissions, crucial in the face of climate change.

The adoption of DA varies globally, driven by economic gains and technological infrastructure. While DA holds immense potential to improve resource management, reduce environmental impact, and enhance crop quality, challenges persist. Limited access to technology, inadequate knowledge among farmers, high implementation costs, and data privacy concerns hinder widespread adoption [9]. Efforts to address these challenges include precision agriculture technologies, alternative energy sources, and climate-smart practices like agroforestry. The World Bank Group actively supports CSA to increase productivity, resilience, and emission reduction, aligning with sustainable development goals.

DA is recognised as a promising solution to meet growing food demand while minimising environmental harm. However, addressing limitations, including equitable access and ethical considerations, is crucial to harness its full potential in mitigating climate change and ensuring food security. Future research should address these limitations by conducting empirical studies on the effectiveness and accessibility of DA technologies, particularly in developing nations. Economic viability, energy requirements, and social and ethical implications should be further investigated. Integration with other sustainable agriculture practices should also be explored to ensure equitable and sustainable implementation. Careful consideration of these factors is crucial to harness the potential of DA in mitigating climate change and achieving food security [8, 9].

3.1.3. Climate and digital policy: In the coming decades, two major technological challenges will define our trajectory: climate change mitigation and digitalisation. Climate change mitigation is guided by well-defined objectives, whereas digitalisation often appears as a self-propelled journey of technological advancement. In 2019, the European Commission introduced the European Green Deal, outlining Europe's climate policy for the foreseeable future. Subsequently, in 2021, the Digital Compass was unveiled to provide a roadmap for Europe's digital transformation [10].

Both climate change mitigation and digitalisation necessitate effective governance. When it comes to climate action, there is an urgent need to expedite the shift towards a low-carbon economy, ensuring inclusivity, especially for the most vulnerable populations and regions disproportionately affected by climate change. Digitalisation, on the other hand, requires guidance to avert adverse consequences like mass surveillance stemming from data monopolies and unequal access to digital technologies. As digitalisation profoundly alters various aspects of our lives, it carries significant disruptive potential, with its benefits and risks intersecting with climate action [10].

3.2. Circular technologies for waste-to-value or circular agriculture

Circular agriculture seeks to convert agricultural waste into valuable resources, minimising waste and promoting sustainability. Key initiatives include:

- Bio-materials from waste: Agricultural residues and food waste can be transformed into bio-based materials for various applications. For example, in Thailand, rice straw can be converted into biodegradable packaging materials, reducing the need for non-renewable resources.
- Biofertilisers: Agri-food waste can be processed into biofertilisers, enriching soil fertility. In Vietnam, organic waste from food processing plants is used to produce biofertilisers, reducing the dependence on chemical fertilisers.
- Waste reduction: Circular practices significantly reduce waste generation. In Indonesia, the recycling of organic waste into compost not only minimises landfill waste but also provides a valuable soil conditioner for farmers.

3.2.1. Waste-to-value agriculture: Transitioning agriculture from linear resource consumption to a circular economy faces key challenges: (1) *Conversion technology*: Success depends on feedstock properties and conditions, with pre-treatment and processes like pyrolysis enhancing results. Challenges involve feedstock composition, high temperatures, and infrastructure; (2) *Business models*: Complex models, financial uncertainties, and stakeholder involvement hinder circular agriculture. Synchronizing supply chains with feedstock and by-product availability is crucial, as is infrastructure and training; (3) *Analytical tools* such as Life Cycle Assessment (LCA) face data and feedstock challenges. Economic evaluation has limited use in waste management; and (4) *Stakeholder involvement*: Success relies on government, farmer, and consumer involvement. Governments can incentivize through policies, while farmers' willingness depends on location, rules, and incentives. Effective communication and collaboration are vital [11].

3.2.2. Sustainable agriculture based on a circular economy: The agriculture sector currently operates on a linear economic model, which is characterised by a one-way flow of resources from extraction to production to disposal, with little emphasis on sustainability and resource conservation, resulting in food waste and greenhouse gas emissions. With sustainability becoming increasingly important globally, agriculture faces challenges due to climate change, population growth, and changing consumer preferences. The circular economy offers a solution to meet these challenges by reducing waste, protecting the environment, and repurposing materials for added value. To implement circular principles effectively, businesses can focus on meeting customer expectations, unlocking new commercial opportunities, strengthening supply chains, and increasing on-farm efficiency. These changes can not only enhance profitability but also contribute to reducing food waste, carbon emissions, and environmental impact, making agriculture more sustainable and environmentally responsible.

For example, a study in Thailand examines user intentions for using mobile technology in agricultural waste valorisation. It identifies two user segments: older users with varying incomes and younger users with lower incomes, with age and income being significant factors. Social influence, price value, and trust impact older users, while privacy matters more to younger users. Habit influences both segments. The study sheds light on the complex interplay of demographic factors and behavioural intentions related to agricultural waste valorisation through digital technology in agricultural sector [12].

4. Case of study: the digital and circular solutions for Vietnamese coffee

The development of INNSA platform aimed to maximise coffee farm productivity by monitoring soil and environmental conditions affecting yield. It is expected to collect real-time data, generates reports, and offers science-backed suggestions for optimal productivity. This promotes efficient resource use, cost control, and sustainable agriculture. Thus, the platform was designed as follows: IoT devices utilising LoRa waves for continuous data collection (e.g., pH, oxidation reduction potential, electrical conductivity, water and air temperature, humidity, light intensity, and NPK levels) and AI for image recognition. The platform leveraged these data sources to offer advice on cultivation, harvest, and pest and disease prevention. The data collected were then transmitted to a computer database for processing, providing real-time insights into cultivation regions (Figure 1).

As a result, we have developed a model and workflows for the INNSA platform, which encompass: (1) A critical examination and review of the coffee supply chain and value chain in Vietnam; (2) The innovative and cost-effective development of the platform with a smart database; (3) The construction of Big Data for the platform, incorporating real-world data inputs for the smart database; (4) The innovative and cost-effective development of value-added products and services within the INNSA platform's value chain and ecosystem; and (5) The systematic integration, evaluation, and analysis of the developed platform and products within the ecosystem [1].

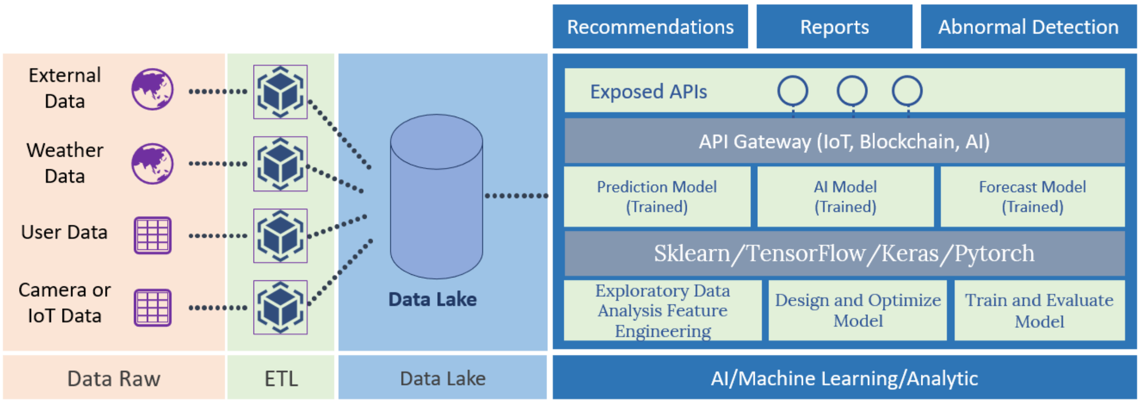

Figure 1. The AI/IoT/Blockchain-powered INNSA platform supports analytical reporting, provides recommendations, and detects anomalies using data collected from various sources.

The INNSA platform model includes the flow of data collected from various sources, its storage in a Data Lake, analysis through Business Intelligence (BI) tools, and integration via a Portal. The model also showcases mobile applications for controlling IoT devices and providing farming recommendations, supported by AI and machine learning technologies. The general workflow of the INNSA platform encompasses a critical investigation and review of the coffee supply chain and coffee value chain in Vietnam, with a focus on key factors, stakeholders, and SWOT analysis.

Based on the critical examination and reviews conducted in the first step, we developed the INNSA platform in the second step. This development included the creation of a supply chain traceability system and various management systems, such as farm production area management, plant information management system (PIMS), supplier information management system (SIMS), and customer and partner relationship management (CRM & PRM). Additionally, we developed E-commerce systems (Web & Mobile applications), IoT devices utilising LoRa waves, and API Gateway systems integrated with Blockchain and AI.

In the third step, the platform constructs Big Data by gathering real-world data inputs essential for smart farming applications. This includes data related to farm soils, environmental conditions, crop information, and market trends. The platform utilises these Big Data insights to drive operational decisions and redesign business processes within the coffee supply chain.

The fourth step involves the development of value-added products and services within the coffee value chain. This includes nanoparticles for coffee preservation, carbon quantum dots and other products made from coffee grounds and waste, sustainable and precision agriculture solutions (e.g., microbial organic fertiliser), IoT devices for data updates, and E-commerce capabilities. These innovations are supported by AI, Blockchain, and supply chain traceability technologies. For example, we have currently improved model accuracy for coffee leaf disease classification using deep learning techniques. By combining various deep convolutional neural networks and employing early and late fusion methods, we aim to boost overall classification performance. Our experiments reveal that the ensemble approach surpasses single-model methods, achieving exceptional accuracy and precision in BRACOL coffee disease leaf classification.

Finally, the INNSA platform and its products undergo systematic integration, evaluation, and analysis within the INNSA eco-systems. This evaluation encompasses laboratory-scale testing and real-world trials on coffee farms and storage spaces, focusing on data collection, smart farming, harvest and post-harvest processing, source traceability, and commercialisation within the coffee supply chain and value chain.

5. Constraints and Questions for future research

The integration of digital and circular technologies in agriculture encounters constraints stemming from factors like limited technological access in remote areas, high implementation costs, concerns about data privacy and ownership, the environmental impact of e-waste, the need for comprehensive training, interoperability challenges, cultural resistance to change, and regulatory frameworks. Moreover, issues related to market access and recycling facilities can affect the effectiveness of circular practices. Balancing the advantages of these technologies with these constraints is crucial for their successful and sustainable adoption in agriculture.

While digital and circular technologies offer immense promise, several critical questions demand further exploration:

- Technology adoption: What are the key barriers that farmers face in adopting digital and circular technologies, and how can these barriers be effectively addressed? Are there successful models yet?
- Scaling up: How can successful pilot projects be scaled up to benefit larger agricultural communities? What are the lessons learned from projects that have successfully scaled, and how can these insights be applied to new initiatives?
- Environmental impact: What is the long-term environmental impact of circular agriculture? How can it be assessed and improved? How do circular practices influence biodiversity and ecosystem health?
- Policy frameworks: What policy frameworks are needed to incentivize the adoption of digital and circular technologies in agriculture?
- Economic viability: Can circular agriculture practices demonstrate economic viability for farmers, thereby ensuring their long-term adoption? What are the business models for these practices?
- Data privacy and security: What regulatory frameworks are required to protect sensitive agricultural data?

- Climate adaptation: How can digital tools be further harnessed for climate adaptation in agriculture, particularly in regions prone to extreme weather events?
- Integration of traditional knowledge: How can traditional farming practices and local knowledge be integrated with modern technologies and contribute to more resilient and sustainable agriculture?

6. Conclusions

The adoption of digital and circular technologies in agriculture represents a significant step towards climate-smart and sustainable farming. These innovations offer a promising path forward, but ongoing research, interdisciplinary collaboration, and partnership among stakeholders are essential to fully realise their potential and address the evolving challenges faced by agriculture in the developing countries and globally. By tackling these questions, we can work toward a future where agriculture is not only resilient to climate change but also sustainable, efficient, and environmentally friendly, ensuring food security and livelihoods for generations to come.

Acknowledgments

The authors would like to thank Vingroup Innovation Foundation (VinIF) under Research Grant No. VINIF.2021.DA00047 for their financial support to VDN. We would also like to express our appreciation to The United Kingdom Royal Society (ICA\R1\191220) and the Royal Academy of Engineering (FF\1920\1\45) for their valuable financial assistance to ANP.

References

[1] Nguyen V D, Pham T C, Le C H, Huynh T T, Le T H, Packianather M 2023 An innovative and smart agriculture platform for improving the coffee value chain and supply chain *Stud. Comput. Intell.* **1068** 185-197

[2] Vu T L, Nguyen V D 2023 An IoT solution designed for remote automatic control and supervisor systems to key environmental factors and diseases in coffee farms in Vietnam *Stud. Comput. Intell.* **1068** 305-317

[3] Giller K E *et al.* 2021 The future of farming: Who will produce our food? *Food Sec.* **13** 1073–1099

[4] Ricciardi V, Ramankutty N, Mehrabi Z, Jarvis L, Chookolingo B 2018 How much of the world's food do smallholders produce? *Glob. Food Security* **17** 64–72

[5] Arbuckle J G Jr, Morton L W, Hobbs J 2015 Understanding farmer perspectives on climate change adaptation and mitigation: the roles of trust in sources of climate information, climate change beliefs, and perceived risk *Environ Behav*. **47** 205-234

[6] Hassoun A *et al*. 2023 Digital transformation in the agri-food industry: recent applications and the role of the COVID-19 pandemic *Front. Sustain. Food Syst.* **7**

[7] Dwivedi Y K *et al.* 2022 Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action *Int. J. Inf. Manag.* **63** 102456

[8] Balasundram S K, Shamshiri R, Sridhara S, Rizan N 2023 The role of digital agriculture in mitigating climate change and ensuring food security: an overview. *Sustainability* **15** 5325

[9] Bahn R A, Yehya A A K, Zurayk R 2021 Digitalization for sustainable agri-food systems: potential, status, and risks for the MENA region *Sustainability* **13** 3223

[10] European Commission (EC) 2021 ‘2030 Digital Compass: the European way for the Digital Decade’, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (https://eur-lex.europa.eu/legal-content/ en/TXT/?uri=CELEX%3A52021DC0118)

[11] Haque F, Fan C, Lee Y Y 2023 From waste to value: Addressing the relevance of waste recovery to agricultural sector in line with circular economy *J. Clean. Prod.* **415** 137873

[12] Pienwisetkaew T, Wongsaichia S, Pinyosap B, Prasertsil S, Poonsakpaisarn K, Ketkaew C 2023 The behavioral intention to adopt circular economy-based digital technology for agricultural waste valorization *Foods* **12** 2341