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Blockchain-enabled carbon footprint traceability in Thailand's organic food sector: A quintuple helix innovation approach

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ABSTRACT

Trustworthy carbon footprint data is increasingly critical for organic food supply chains, yet many existing systems lack transparency, credibility, and cross-sector integration particularly in emerging economies. This research aims to develop a blockchain-based traceability system that addresses these gaps through a sustainability-driven, multi-stakeholder approach. Grounded in the Quintuple Helix Innovation (5HI) model, the study incorporates perspectives from government, industry, academia, civil society, and environmental actors to co-create a Minimum Viable Product (MVP) tailored to Thailand's organic agriculture sector. Data were gathered from in-depth interviews with key stakeholders including farmers, processors, logistics providers, retailers, certifiers, regulators, system developers, and consumers supported by document analysis of relevant agricultural, climate, and blockchain-related policies. The resulting MVP integrates mobile applications, IoT sensors, and blockchain verification for real-time carbon tracking and transparent certification. The originality of this study lies in operationalizing the 5HI framework into a practical, participatory MVP design that merges technical feasibility with environmental and institutional accountability. Findings show promise in reducing certification fraud and enhancing traceability legitimacy, although implementation challenges such as interoperability, startup costs, and rural access persist. This work contributes a replicable model for sustainable digital transformation in agri-food innovation.

1. Introduction

The global agri-food industry is increasingly challenged by issues related to environmental sustainability, greenhouse gas (GHG) emissions, and food safety. Food production contributes significantly to climate change, accounting for approximately 21–37 % of global GHG emissions (Rosenzweig et al., 2020). Concurrently, recurrent food safety incidents, including pesticide contamination and microbial outbreaks, have heightened consumer awareness and demand for improved transparency throughout food supply chains (Treiblmaier and Garaus, 2023; Yang et al., 2019). To mitigate those issues, the European Union has introduced the Digital Product Passport (DPP), designed to enhance traceability and transparency by digitally documenting product lifecycles across multiple sectors (European Commission, 2023).

These concerns are particularly pronounced in regions such as Southeast Asia, where the agricultural sector plays a crucial economic and social role. Moreover, these global challenges manifest with intensity due to the region's significant agricultural dependence and export orientation. In response to these pressing issues, ASEAN (Association of Southeast Asian Nations) regional policy initiatives have increasingly prioritized the development of robust traceability systems. Consumer behavior within the ASEAN region underscores the importance of verifiable sustainability practices. Recent market analyses indicate that 83 % of ASEAN consumers express skepticism about the authenticity of organic certifications that are not digitally verified (NielsenIQ, 2024). Furthermore, carbon footprint labeling has shown potential in influencing consumer choices towards more environmentally responsible products by up to 20 % (Camilleri et al., 2019).

Similarly, Thailand has implemented the Carbon Footprint for Product (CFP) initiative, managed by the Thailand Greenhouse Gas

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Management Organization (TGO), certifying thousands of products to promote transparency regarding their environmental impact (TGO, 2024). Despite Thailand's significant growth potential within the organic export sector, the industry remains vulnerable due to fragmented supply chains, inconsistent regulatory compliance, and limited digital capabilities among small and medium-sized enterprises (SMEs) (Sundram, 2023). Addressing these structural weaknesses requires not only regulatory improvements but also technological innovations that can ensure data transparency and credibility across the food value chain.

Blockchain technology has emerged as a promising tool to address these transparency and verification challenges. Its capacity to securely record and share immutable transaction data across supply chain actors positions it as an ideal technology for verifying carbon emissions, certifying organic status, and enhancing food safety (Saberi et al., 2019; Bager et al., 2022). The technology's alignment with emerging policy frameworks such as the EU's DPP (Digital Product Passport) and Thailand's CFP (Carbon Footprint Product) labeling schemes further strengthens its strategic relevance. However, blockchain adoption faces numerous implementation hurdles in developing economies. In Thailand, barriers include limited digital infrastructure, high initial setup costs, and regulatory misalignments, which have prevented widespread adoption among SMEs (Jayaraman et al., 2024). While blockchain is widely recognized for its potential to enhance transparency, traceability, and trust in food supply chains, Ellahi et al. (2023) and Köhler and Pizzol (2020) indicate that many benefits attributed to blockchain are the result of broader digitalization. All impacts are not directly attributable to blockchain itself.

Current literature reveals critical gaps that limit effective blockchain implementation in food traceability systems. First, comprehensive frameworks integrating blockchain with complementary technologies such as IoT remain underdeveloped, with limited exploration of technological synergies (Kaur et al., 2022). Second, existing studies typically examine technical or economic aspects in isolation, lacking holistic assessments that consider socio-economic, regulatory, and infrastructural diversity particularly in developing regions (Erol et al., 2020; Tang et al., 2024). Third, empirical studies evaluating real-world blockchain implementations in food systems remain scarce, with insufficient investigation of adoption barriers including organizational resistance, knowledge gaps, and implementation costs (David et al., 2022; Friedman and Ormiston, 2022).

To address these multifaceted challenges, this research adopts the Quintuple Helix Innovation (5HI) model as a theoretical framework. The 5HI model integrates five key innovation actors which are government, academia, industry, civil society, and the natural environment, fostering collaborative approaches to technology adoption through cross-sector engagement, institutional learning, and context-responsive governance (Borrero and Yousafzai, 2024; Eiselein and Langenus, 2025). These insights underscore the necessity for interdisciplinary research and the development of integrated, context-aware frameworks to guide the effective adoption and assessment of blockchain-based innovations in food traceability.

This research addresses the following research questions,

RQ1. : How can a Minimum Viable Product (MVP) framework be designed to align blockchain-based traceability systems with the operational, technological, and regulatory requirements of Thailand's organic food sector?

RQ2. : What factors influence the feasibility of implementing a blockchain-based carbon footprint traceability model in Thailand's organic food sector, particularly with respect to technical readiness, market acceptance, financial sustainability, and organizational capabilities?

In response to these questions, this research aims to (1) propose a Minimum Viable Product (MVP) framework tailored to the operational, technological, and regulatory requirements of Thailand's organic food sector; (2) evaluate the feasibility of implementing a blockchain-based carbon footprint traceability model by examining technical readiness, market acceptance, financial sustainability, and organizational capabilities. Together, these objectives support a context-responsive approach to digital sustainability, with implications for policy, innovation management, and regional competitiveness. This research contributes to the intersection of digital innovation, sustainability science, and agricultural development by providing a theoretically grounded, empirically informed approach to blockchain adoption in developing economy contexts. The study's significance lies in its integration of technological feasibility with stakeholder collaboration theory, offering practical guidance for policymakers, industry practitioners, and development organizations seeking to implement blockchain-based sustainability solutions. Furthermore, by focusing on Thailand as a representative case within Southeast Asia's agricultural export sector, the findings provide insights with broader regional applicability for similar developing economies transitioning toward digital sustainability frameworks.

The following sections detail the methodology and data analysis approach, followed by results, discussion, and conclusions that address both theoretical contributions and practical implications for blockchain-enabled food traceability systems.

2. Literature review

Enhancing transparency and carbon accountability in Thailand's organic food supply chains demands approaches that integrate technological innovation with institutional, social, and environmental dimensions. Literature on blockchain traceability highlights its potential for improving certification integrity and stakeholder trust, while also revealing persistent challenges related to cost, interoperability, and governance. Drawing on Actor-Network Theory (ANT) and the Quintuple Helix Innovation (5HI) framework, this review synthesizes insights to guide the co-creation of a Minimum Viable Product (MVP) for sustainable and inclusive carbon footprint tracking.

2.1. Blockchain traceability in food supply chains

Blockchain technology is transforming food supply chains by tackling key challenges related to transparency, food safety, and sustainability across complex systems involving multiple stakeholders. When combined with Industry 4.0 technologies such as cloud computing, big data analytics, radio frequency identification, the Internet of Things, sensors, near-field communication, artificial intelligence, machine learning, and global positioning systems, blockchain significantly improves traceability in food supply chains (Menon and Jain, 2024). In the context of Thailand's organic food sector, blockchain builds consumer trust, minimizes certification fraud, and supports regulatory compliance. Its decentralized and immutable ledger enables comprehensive traceability and integrates seamlessly with Internet of Things devices like radio frequency identification tags and sensors to facilitate real-time data collection (Feng et al., 2020). Within Thailand's broiler supply chain, blockchain applications strengthen risk management and improve coordination among stakeholders, positioning the technology as a socio-technical innovation for organic supply systems.

Table 1 highlights five critical gaps in blockchain-based carbon footprint (CFP) traceability research and introduces key features, ensuring both technical feasibility and alignment with regulator-grade standards. It integrates four essential components, systematic literature reviews, CFP scheme development, Measurement, Reporting, and Verification (MRV) design, and policy framework alignment. This positions the study as a pioneering contribution to Thailand's organic sector. Notably, it is the first blockchain-based MVP focused on CFP to incorporate MRV protocols and standards such as GS1 EPCIS 2.0 and the European Union's Digital Product Passport (DPP). Explicitly, blockchain's innovative capabilities lie in its ability to deliver high

Table 1
Key insights and gaps in existing literature.

Focus area	Key insights from existing literature	Identified gaps
Blockchain in food supply chains	Reviews show blockchain improves transparency & traceability but focus largely on technical feasibility; limited empirical adoption evidence (Kayikci et al., 2022; Bumblauskas et al., 2020).	CFP-specific applications are rarely analyzed; socio-economic and regulatory dimensions underexplored.
Blockchain for carbon footprint accounting	Studies highlight potential for immutable carbon inventories, provenance/versioning, and audit trails (Kouhizadeh et al., 2021; Wang et al., 2023).	Lack of integrated frameworks linking blockchain to CFP certification in real-world agri-food systems.
MRV and verification mechanisms	Conceptual work on smart contracts, proofs, and auditor workflows exists (Patel et al., 2024a; Zhang et al., 2024).	Few applied designs for MRV-ready verification in developing economy food chains.
Standards and policy frameworks	GS1 EPCIS 2.0 and EU Digital Product Passport offer regulator-grade structures for traceability (GS1, 2022a; European Commission, 2023).	Rarely integrated into CFP-oriented blockchain pilots; most studies remain policy-agnostic.
Limitations in adoption studies	Existing work often examines technical or cost factors in isolation (Friedman and Ormiston, 2022b).	Fragmented analysis of barriers in SMEs and developing contexts; limited participatory co-design approaches.

traceability accuracy, reduce certification fraud, and boost consumer confidence. Smart contracts automate verification processes, ensuring compliance with standards like Thailand's Organic Agriculture Certification, while carbon footprint tracking supports sustainability goals (Saberi et al., 2019; Ellahi et al., 2023). Blockchain-based carbon tracking enables immutable carbon inventories, factor provenance, and audit trails, strengthening MRV systems (Kouhizadeh et al., 2021; Wang et al., 2023; Patel et al., 2024a).

Despite its potential, blockchain adoption faces challenges, including scalability issues in public blockchains, interoperability with SME legacy systems, and data privacy concerns in permissionless networks (Lei et al., 2022). High implementation costs further limit deployment in Thailand's SME-dominated organic sector. However, advancements such as AI and IoT integration, cross-chain architectures, and privacy-preserving techniques like zero-knowledge proofs enhance blockchain's applicability (Patel et al., 2024b; Lei et al., 2022). Standards like GS1 EPCIS 2.0 and the EU DPP provide robust frameworks for regulator-grade blockchain carbon data, though their integration into food traceability systems remains limited (GS1, 2022b; European Commission, 2023). Cost-effective blockchain models from Thailand's broiler supply chain offer a promising blueprint for organic food traceability, reinforcing blockchain's role as a transformative tool for sustainable and transparent supply chains.

2.2. Blockchain adoption and open innovation in Thai organic food SMEs

Blockchain technology presents Thai organic food SMEs with a viable pathway to overcome chronic resource constraints, including limited capital, technical expertise, and absorptive capacity, which often hinder innovation in fragmented supply chains. By leveraging blockchain's decentralized architecture, small producers can reduce coordination costs and address trust deficits across multi-actor networks. This approach aligns with ambidextrous strategies that balance the exploitation of existing competencies with the exploration of emerging digital practices proposed by AlShaygy (2025). The integration of smart contracts into certification and traceability systems has been shown to reduce negotiation and monitoring costs by half, making these services more accessible to SMEs and enhancing supply chain resilience (Lumineau et al., 2021).

The principles of open innovation further amplify blockchain's benefits by enabling SMEs to access external knowledge and resources without requiring substantial upfront investment. Platform-based ecosystems provide entry to complementary services such as certification, logistics, and marketing. These ecosystems foster knowledge spillovers and peer learning, helping to address gaps in absorptive capacity while facilitating collective action to influence industry standards and promote inclusive governance models (Parker et al., 2016; Hagiu and Wright, 2015). Evidence reinforces that blockchain-enabled ecosystems not only optimize operational efficiency but also enhance collaborative innovation processes, especially in resource-constrained SMEs (Sayal et al., 2023; Hadi, Almessabi and Khan, 2025).

The incorporation of carbon accounting protocols into blockchain platforms adds another layer of value for Thai organic SMEs. Verified on-chain credentials support participation in emerging carbon credit markets tailored for smallholders, enabling firms to monetize sustainability practices and potentially increase revenue by up to 34 percent (Saberi et al., 2019). Tiered service models and hybrid architectures that combine on-chain verification with off-chain sensor data offer scalable, cost-effective solutions for SMEs, aligning technological adoption with incremental learning pathways (Baldwin and Clark, 2000).

The effective orchestration of open innovation in this context depends on intermediary organizations such as cooperatives, industry associations, and government agencies. These entities play a crucial role in resource pooling, capability development, and platform governance, which are essential for overcoming adoption barriers highlighted in recent research (Tangsakul and Sureeyatanapas, 2024; Rahman et al., 2025). Furthermore, frameworks emerging emphasize multi-helix collaboration—linking industry, academia, government, civil society, and environmental stakeholders—to co-create sustainable solutions (Ketkaew et al., 2024; Padthar and Ketkaew, 2024). By integrating blockchain's technical features with open innovation strategies coordinated through such intermediaries, Thai organic food SMEs can achieve inclusive, scalable, and sustainable transformation across their agri-food ecosystems.

2.3. Stakeholder dynamics through actor-network theory (ANT)

Actor-Network Theory (ANT) offers a robust framework for understanding how blockchain traceability systems are co-constructed through dynamic interactions between human and non-human actors. ANT moves beyond linear adoption models by focusing on how agency is distributed across the network,including technologies, institutions, and users. The core translation processes in ANT namely problematization, interessement, enrollment, and mobilization, explain how networks are formed, stabilized, and transformed (Callon, 1986; Latour, 2005). Unlike the Technology Acceptance Model (TAM), which focuses on individual decision-making, or traditional Supply Chain Management (SCM) theories that emphasize operational efficiency, ANT highlights how technical elements like smart contracts or IoT sensors possess functional agency. These non-human actants, such as Hyperledger Fabric or RFID systems, enable traceability and data immutability, reinforcing trust and verification in decentralized food systems (Kshetri, 2021).

In contrast to models that view stakeholders as passive adopters, ANT enables a more nuanced understanding of how human actors, including farmers, manufacturers, logistics providers, retailers, consumers, and regulators, participate in shaping traceability ecosystems. Existing studies emphasize the role of intermediaries such as agricultural cooperatives and certification bodies in enhancing transparency and reducing fraud in emerging market contexts (Liu et al., 2023). However, literature gaps remain regulatory frameworks are treated as static, and the socio-technical integration of carbon accounting is underexplored.

ANT allows to map interactions between technological, regulatory, and environmental actants, which is critical for CFP-traceability design. For instance, widespread mobile usage and QR code-based traceability apps have contributed to increased consumer engagement, but their role in stabilizing trust and legitimacy remains underexplored. ANT allows for mapping interactions between both technological and regulatory actants such as Thailand's Organic Agriculture Standard (TAS 9000 2009), mobile based data systems, and carbon accounting protocols, providing a systems level perspective aligned with broader applications in agriculture like seafood traceability and precision farming (Astill et al., 2019).

Despite its strengths, the literature on blockchain in agri-food traceability tends to treat regulatory frameworks as static rather than negotiated, failing to capture the performative role of institutions in legitimizing technical systems (Duan et al., 2024). Regulatory agencies, such as the Thailand Greenhouse Gas Management Organization (TGO) and the Food and Drug Administration (FDA), function as obligatory passage points in shaping traceability standards (Latour, 2005), yet are often overlooked in system design literature. Similarly, while blockchain interoperability and privacy challenges are discussed (Zhang et al., 2024), few studies analyze how these technical infrastructures reconfigure governance and accountability relationships across stakeholder groups. ANT thus provides a critical lens to understand how innovation is not simply adopted but constructed through actor alignments and translation processes across technological and institutional boundaries (Gallo et al., 2021; Michaelidou and Hassan, 2008). Given these dynamics, there is a growing need to complement ANT with participatory frameworks that emphasize cross-sector collaboration and co-creation. This necessitates a shift toward more inclusive models such as the 5HI framework, particularly when integrated with agile tools like Minimum Viable Product (MVP) development, as discussed in the next section.

2.4. Synergizing quintuple helix innovation (5HI) and minimum viable product (MVP)

Open innovation involves integrating knowledge flows across organizational boundaries to co-develop solutions beyond internal R&D (Sá et al., 2023; Majchrzak et al., 2023; Huang and Zhou, 2025). It promotes collaboration among firms, research institutions, users, and external partners to overcome internal resource constraints and accelerate innovation. In agricultural settings, it supports stakeholder inclusion, from smallholder producers to regulators and consumers, enabling more localized, adaptive, and sustainable solutions. This principle aligns with the development of blockchain-based carbon footprint traceability, which requires ecosystem-wide coordination and stakeholder trust to ensure both technical performance and legitimacy. The Minimum Viable Product (MVP) framework fits naturally within open innovation. It facilitates rapid prototyping and iterative improvement by incorporating early user feedback and leveraging open-source tools (Alonso et al., 2019). Especially in uncertain and complex environments, MVP development enables teams to prioritize user needs and reduce time-to-market (Bagherzadeh et al., 2021). In Thailand's organic food sector, this process allows for early-stage testing of blockchain traceability models that must meet diverse user expectations, from farmers inputting cultivation data to consumers verifying product authenticity.

The Triple Helix Innovation (3HI) model provides a foundational perspective on open innovation through the interaction of three core institutional spheres: academia, government, and industry. It emphasizes knowledge-based development by fostering synergy among these actors to stimulate regional innovation ecosystems and enhance policy relevance and technological commercialization (Lopes et al., 2021). In food system innovation, this model has proven effective in mobilizing regional talent, aligning research agendas with industrial needs, and enhancing the local relevance of public R&D (Mayho et al., 2024). However, 3HI frameworks tend to underrepresent societal engagement and sustainability concerns by prioritizing economic and technological outputs, while overlooking social and ecological dimensions. As such, 3HI serves as a structural precondition but requires extension to meet the demands of inclusive and sustainable innovation.

The Quadruple Helix Innovation (4HI) model addresses these limitations by introducing civil society as a fourth helix alongside government, academia, and industry. It enables participatory governance, public legitimacy, and user-driven innovation, which are critical for domains like food traceability, where behavioral change and transparency are central (Starkbaum et al., 2024; Stephens, 2025). In the context of blockchain-based traceability, 4HI supports stakeholder co-creation through shared decision-making processes that incorporate grassroots actors such as consumer groups, farmer cooperatives, and local NGOs. This co-creation is particularly valuable in Thailand's organic food sector, where trust, digital literacy, and institutional alignment are crucial to adoption. While 4HI offers a more inclusive and policy-embedded approach than 3HI, its scope remains limited when innovation outcomes must account for long-term environmental resilience and systemic sustainability.

The Quintuple Helix Innovation (5HI) model offers a valuable framework for addressing the intersecting social, institutional, and environmental challenges that arise in sustainability-focused innovation. By introducing the natural environment as a fifth helix alongside academia, industry, government, and civil society, the model encourages a more holistic approach to innovation as an eco-social process (Borrero and Yousafzai, 2024). This is particularly relevant for initiatives like carbon footprint traceability and circular economy transitions, where both technological and ecological considerations must be integrated from the outset (Gallo et al., 2021; Michaelidou and Hassan, 2008). The eco-5HM model, for example, further develops this idea by clarifying the sustainability roles and priorities of different stakeholders within environmental innovation systems (Van Bueren et al., 2025). In this study, the principles of 5HI are reflected in the design and implementation of the blockchain-based traceability system through the inclusion of five key stakeholder groups (see Fig. 1):

- **Academia** shaped the research design and digital architecture, with researchers and IT developers providing technical input and guiding the MVP development based on institutional knowledge and prior studies.
- **Industry** offered operational insights through the involvement of organic food manufacturers, logistics providers, and retailers, helping ensure that the system aligned with real-world supply chain practices and market expectations.
- **Government** influenced regulatory and compliance aspects by contributing frameworks for organic certification, digital food safety (e.g., FDA), and data privacy (e.g., PDPA), all of which helped define the system's legal and procedural boundaries.
- **Civil Society** informed adoption and user experience considerations, as farmers and consumers highlighted challenges related to digital literacy, trust, and accessibility.
- **Natural Environment** guided the ecological dimension of the system through references to carbon measurement protocols, climate policy instruments, and sustainability benchmarks, including the TGO GHG Methodology Manual and the Thailand Climate Change Master Plan.

This study developing a CFP-focused, 5HI-guided MVP framework, integrating technical, socio-institutional, and environmental dimensions, while grounding the system in MRV protocols and recognized standards. The use of 5HI also aligns with Actor-Network Theory (ANT), which provides insight into how both human and nonhuman actors, such as digital platforms, certification protocols, and data infrastructures, co-construct innovation outcomes (Eiselein and Langenus, 2025). Together, 5HI and ANT offer a grounded yet adaptable lens for understanding how innovations evolve across institutional and ecological landscapes. Building on these foundations, this study integrates

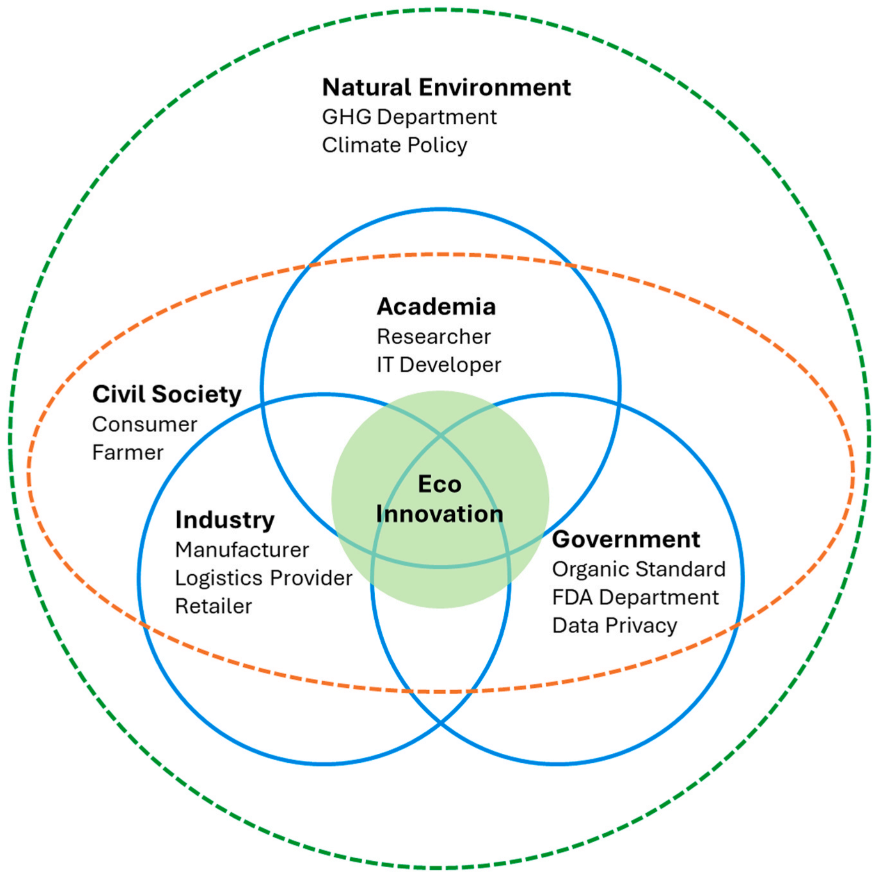

Fig. 1. Quintuple helix innovation (5HI) model for blockchain-enabled carbon footprint traceability.

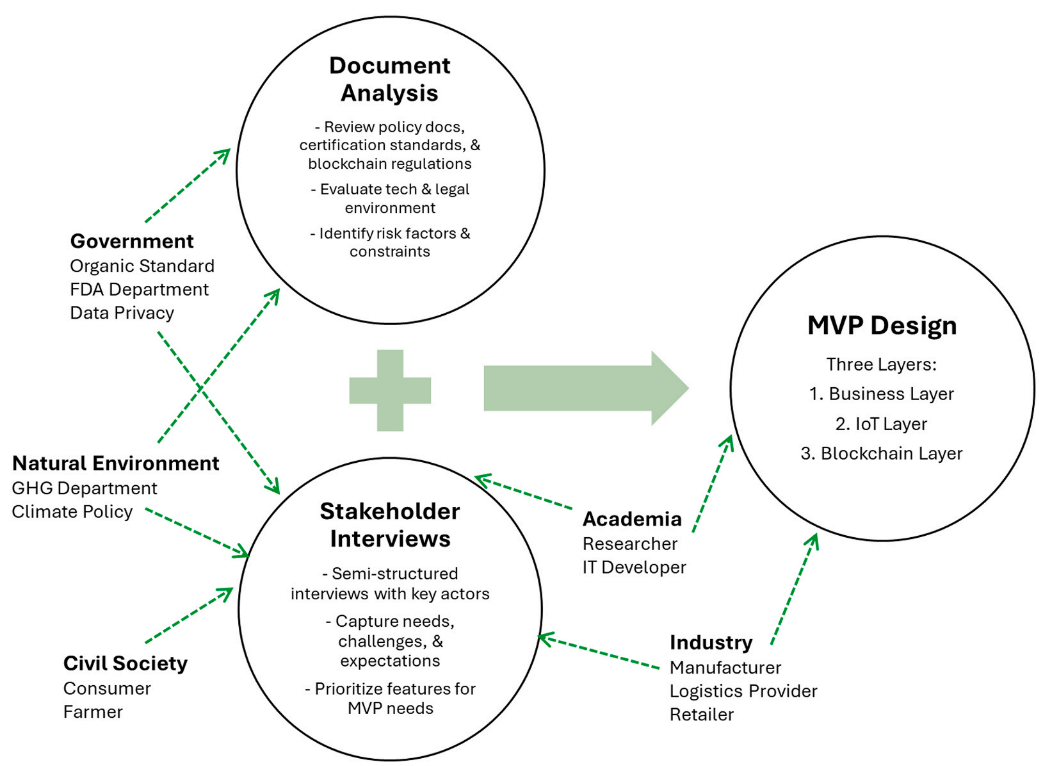

Fig. 2. Research Framework Integrating 5HI Model with MVP Development.

open innovation's user-centered development logic for MVP with the governance and sustainability lens of 5HI to promote a blockchain traceability system that is not only technically feasible and market-relevant, but also ecologically responsible, socially inclusive, and aligned with broader sustainability goals.

3. Methodology

3.1. Research framework

The research framework (Fig. 2) sets out a clear process for developing a blockchain-based carbon footprint traceability system in Thailand's organic food supply chain. It starts with document analysis of agricultural policies, certification standards, and blockchain regulations to define the legal, operational, and technical boundaries for system design, including issues of interoperability and governance (Bowen, 2009; Casino et al., 2019). This is followed by stakeholder interviews with farmers, manufacturers, logistics providers, retailers, certifiers, and regulators to understand practical needs, perceived challenges, and shared priorities, with thematic analysis applied to identify patterns that inform the MVP (Freeman et al., 2020; Braun and Clarke, 2021). The MVP is organized into three layers: business (roles, workflows, decision-making), IoT traceability (real-time data capture through RFID, sensors, and mobile apps), and blockchain (immutability, smart contracts, certification transparency). Each stage of this process reflects the 5HI model, bringing together academic expertise, industry practices, government oversight, civil society perspectives, and environmental priorities to ensure the system is grounded in both practical application and sustainability goals.

3.2. Document analysis

Document analysis systematically examines and interprets texts (Morgan, 2022). Using Schreier's Qualitative Content Analysis, this study reviewed 8 documents covering policies, certification standards, and regulations relevant to blockchain-based carbon footprint systems. The analysis synthesized the legal, regulatory, and technical environment; identified risk factors and operational challenges; and mapped nonhuman actors such as policy frameworks, data standards, and digital platforms, in line with ANT and Open Innovation principles. These insights informed the co-creation and assessment of the MVP. Documents were purposively selected for relevance, issuing authority, and alignment with stakeholder needs identified through interviews. They were categorized into: (1) national policies, (2) organic certification standards, (3) blockchain and data regulations, and (4) technical implementation reports, sourced from official agencies, certification bodies, and recognized institutions. Following Morgan's (2022) steps, documents were read for scope, coded into themes and organized into a matrix mapping these themes to stakeholder requirements and potential MVP features. This process revealed policy-driven design constraints, mandatory data requirements, and technical limitations. Table 2 lists the reviewed documents, including Thailand's Agriculture Policies and Development Strategies, ETDA Guidelines on Blockchain Adoption, FDA Digital Food Safety Guidelines, and IFOAM Norms, which define the system's legal, technical, and ethical boundaries.

3.3. Stakeholder interviews

An inductive qualitative approach within a multi-phase research framework was used to examine the development of a blockchain-based carbon footprint traceability system in Thailand's organic food sector. Guided by ANT, the study mapped human and non-human actors in the traceability ecosystem, recognizing their interconnected roles in shaping innovation. Participants were recruited through a combination of purposive and snowball sampling to ensure representation across the supply chain and inclusion of actors with technical, regulatory, operational, and consumer influence. A total of 40 participants were recruited, consistent with qualitative saturation ranges of 20–50 (Guest et al., 2006), with ANT-based actor mapping informing selection.

Farmers ($n = 10$) were recruited via cooperatives, manufacturers ($n = 3$) were purposively chosen for export compliance, logistics/retailers ($n = 6$) were selected through a mix of purposive and snowball methods, regulators (TGO) ($n = 3$) were purposively chosen, consumers ($n = 15$) were referred via retailer networks, and traceability system developers in academia ($n = 5$) were selected for technical expertise. These participants were chosen not only for their sectoral relevance but also for their network influence and interaction with non-human actants such as certification protocols, carbon tracking methods, QR-code systems, and blockchain infrastructure. For example, TGO functioned as an "obligatory passage point" for compliance and carbon data validation (Latour, 2005), while blockchain developers acted as intermediaries translating system requirements into platform architecture.

Semi-structured interviews were conducted in person or via video conferencing (e.g., Zoom, Skype for Business) (Braun and Clarke, 2021),

Table 2
List of blockchain carbon footprint related documents.

Document Type	Title	Year	Law/Rule/Regulation	Authority	Main Points related to Blockchain Carbon Footprint System
Policy Document	Thailand Agriculture Policies and Development Strategies	2019–2021	National Strategy	Ministry of Agriculture and Cooperatives (MOAC)	Promotes digital platforms for organic traceability and farm certification support.
Certification Standard	Certification Alliance Organic Standard	2021	Organic Certification Requirement	Organic Agriculture Certification Thailand (ACT)	Outlines traceability and audit trail requirements in organic certification processes.
Regulation	Personal Data Protection Act (PDPA)	2019	Data Protection Law	Ministry of Digital Economy and Society (MDES)	Specifies data consent, encryption, and governance essential for blockchain systems.
Methodological Guideline	TGO GHG Methodology Manual for Agricultural Sector	2023	Carbon Accounting Standard	Thailand Greenhouse Gas Management Organization (TGO)	Details GHG emission factors and reporting templates for blockchain-compatible data logs.
Regulatory Framework	ETDA Guidelines on Blockchain Adoption	2022	Blockchain Governance Standard	Electronic Transactions Development Agency (ETDA)	Defines legal and technical conditions for blockchain usage across sectors.
Compliance Guideline	FDA Digital Food Safety Guidelines	2020	Digital Compliance Protocol	Food and Drug Administration (FDA)	Advocates for blockchain-based audit trails and food safety monitoring.
Export Standard	IFOAM Norms for Organic Production and Processing	2020	International Export Standard	International Federation of Organic Agriculture Movements (IFOAM)	Encourages international interoperability of organic certification through traceability.
Climate Policy	Thailand Climate Change Master Plan	2015–2050	National Low-Carbon Policy	Office of Natural Resources and Environmental Policy and Planning (ONEP)	Supports blockchain for carbon tracking aligned with national GHG reduction targets.

each lasting 45–60 min. The protocol covered demographics, operational practices, barriers, and expected outcomes, with a specific focus on platform requirements such as interface design, data accessibility, and interoperability. Questions were adapted from Cooper and Vlaskovits (2013) and informed by lean innovation principles to enable iterative feedback for MVP development. Methodological rigor was maintained using the Consolidated Criteria for Reporting Qualitative Research (COREQ) (Tong et al., 2007), which informed protocol design, researcher reflexivity, data handling, and analytical transparency. The completed COREQ checklist is provided in Appendix A.

3.4. Data analysis

This study employed a structured qualitative analysis process rooted in thematic analysis and guided by the theoretical frameworks of Actor Network Theory and the Quintuple Helix Innovation model. The primary data source consisted of semi-structured interviews with a diverse group of stakeholders, totaling forty participants. To ensure analytical rigor, a systematic coding process was conducted by two researchers. The primary researcher, who has expertise in blockchain technology, collaborated with a secondary researcher specializing in qualitative methods. Together, they completed a comprehensive calibration process that included a joint review of the Actor Network Theory framework and key blockchain terminology. Each researcher independently coded a sample of eight interview transcripts, representing twenty percent of the dataset. They then met to compare and discuss coding differences in order to align their interpretations. Based on this discussion, the codebook and coding guidelines were refined.

Intercoder reliability was assessed using multiple established measures, yielding strong agreement: Cohen's $\kappa = 0.76$ (substantial agreement) for main thematic categories, Krippendorff's $\alpha = 0.79$ (acceptable reliability) for detailed sub-themes, and Holsti's coefficient = 0.82 (high agreement) for the presence/absence of key themes. These scores meet or exceed accepted thresholds for qualitative research reliability (Krippendorff, 2022).

All interview data were transcribed and analyzed using NVivo version 12. A hybrid approach combining inductive and deductive thematic analysis was applied, following the methodology outlined by Fereday and Muir-Cochrane (2006). The inductive coding process allowed themes to emerge directly from the data, capturing stakeholder-specific insights related to trust, usability, and operational challenges. The deductive coding process was guided by the four moments of translation in Actor Network Theory, which include problematization, interessement, enrollment, and mobilization. This framework provided a structured lens for analyzing the interactions between human and non-human actors within the socio-technical system (Callon, 1986).

3.5. Data integration and expert validation

The technical validation cohort comprised five experts, including two traceability system developers from academia and three independent practitioners from the private sector. This composition was designed to blend cutting-edge research perspectives with practical industry experience. To ensure objectivity, the two academic developers (one of whom is an author of this study) participated in the validation interviews as domain experts, but their data was coded and analyzed by the secondary researcher to mitigate confirmation bias. The total sample size of five technical experts follows established precedents in qualitative and expert-based research. The principle of diminishing returns in expert reviews indicates that 3–5 experts can identify the majority of core issues (Patton, 2014). This is supported by recent blockchain-specific studies: Kshetri (2021) used n = 4 experts for feasibility assessment; Zhang et al. (2024) used n = 3 for smart contract validation; and Duan et al. (2024) utilized n = 5. Furthermore, technical expert interviews are known to reach concept saturation rapidly, often within 3–6 interviews (Guest et al., 2006).

A dual-validation approach was explicitly designed to separate technical architecture assessment from user requirement gathering, thereby mitigating construct validity risks. Technical Experts (n = 5, including blockchain developers) evaluated specialized architectural components (e.g., permissioned chains, smart contract design). Their input was confined to areas requiring deep technical expertise. Non-Technical Stakeholders (farmers, processors, etc.) were not asked to evaluate technical constructs. Instead, they provided insights on functional needs, user experience, and adoption barriers, informing the business and interface layers. Regulators and Certifiers served as "boundary spanners" (Star and Griesemer, 1989), bridging technical and operational perspectives due to their hybrid expertise.

Findings from interviews were triangulated with data from the document analysis phase. Technical expert recommendations were cross validated against regulatory documents (e.g., ETDA Guidelines, PDPA) and international standards (e.g., ISO 14067). Operational stakeholder needs were verified against certification standards (e.g., IFOAM Norms) and policy documents. This process ensured alignment between stakeholder claims, regulatory requirements, and documented infrastructure capabilities.

The synthesis of data informed a Minimum Viable Product (MVP) through a competency-aligned validation process. Blockchain architecture decisions were validated exclusively by the technical experts. Governance structures and operational workflows were validated by the relevant domain experts (e.g., farmers for production data, regulators for compliance).Integration between layers was achieved through iterative feedback loops, where technical specifications were translated from operational requirements and reviewed for functional adequacy. This structured approach ensures that all technology-specific claims are grounded in appropriate technical expertise, while user-centric features reflect authentic stakeholder perspectives, resulting in a robust and validated socio-technical architecture.

4. Results

This section presents the main findings and discussions in accordance with the research framework Integrating 5HI Model with MVP Development.

4.1. Regulatory and technical insights

This section synthesizes findings from a systematic document analysis assessing Thailand's regulatory and technological landscape for blockchain-enabled carbon traceability in organic supply chains. Through purposive sampling and thematic analysis of eight key policy documents, this study identified critical requirements shaping the development of a blockchain-based traceability solution for sustainable agriculture. The themes generated from the analysis, as shown in Table 3, were connected to system requirements and mapped to recommended technical features.

Thailand's agricultural policies (2019–2021) promote digital solutions for farmers, emphasizing accessible traceability systems. In response, the solution includes a mobile-friendly interface for real-time farm data recording. This aligns with the Certification Alliance Organic Standard (2021), which requires verifiable tracking from production to certification. To ensure transparency, the system incorporates smart contracts for certification processes. Data protection is addressed through compliance with Thailand's PDPA (2019), which mandates user consent and secure data management. The solution meets these requirements through a permissioned blockchain model that allows controlled data access and encrypted storage. For environmental accountability, the TGO GHG Methodology (2023) provides standardized emission calculations, enabling integration of a blockchain-based carbon calculator to support accurate and auditable emission reporting across the supply chain. Regulatory compliance is further ensured through adherence to the ETDA's Blockchain Guidelines (2022), which

Table 3
Themes identified through document analysis.

Document theme	System requirements	Recommended solution features
Organic Policy and Digital Agriculture	Promote accessible digital traceability tools aligned with national strategies	Mobile-friendly blockchain system for organic farm data logging
Organic Certification Standards	Ensure end-to-end traceability with verifiable and auditable certification data	Real-time certification dashboard with smart contract audit trails
Data Protection and Privacy	Comply with data privacy laws and secure, consent-based data exchange	Permissioned blockchain with user-controlled data access and encryption
Carbon Footprint Methodology	Adopt standardized GHG emission calculation compatible with blockchain	Carbon calculator module with activity-specific emission factors linked to blockchain
Blockchain Legal Framework	Align blockchain systems with legal deployment standards and digital identity validation	ETDA-compliant backend, digital signature support, and secure smart contract environment
Food Safety and Compliance	Support digital, traceable inspection systems for food safety monitoring	Digital inspection workflows with QR-based logging and smart contract-enabled audit trails
International Organic Standards	Ensure interoperability of blockchain traceability with global organic certification standards	Certification module with cross-standard metadata and integration with IFOAM norms
Climate Policy and GHG Tracking	Align traceability and carbon monitoring with climate policy and GHG reduction targets	Carbon credit tracker and policy-aligned reporting dashboard
Interoperability	Adopt international data standards to enable cross-platform traceability and prevent isolated custom integrations	GS1 EPCIS 2.0 and CBV standards spine; identifier strategy using GTIN, GLN, and lot/serials; standardized capture/query APIs; schema versioning and governance mechanisms; mapping of blockchain records to CFP/DPP report fields
System Scalability	Address large-scale deployment requirements by defining performance, cost, and resource parameters	Throughput and latency benchmarks; batching and partitioning methods; blockchain ledger tuning; cloud-based scaling options; transparent operating cost model

define technical standards for digital signatures and smart contracts. The system also incorporates FDA food safety requirements (2020), including digital audit trails and inspection tools, using smart contracts and QR-code tracking for real-time monitoring.

The design also considers international standards, following IFOAM Norms (2020) to ensure global compatibility in organic certification. This facilitates export opportunities by aligning with both Thai (e.g., ACT) and international frameworks. Finally, the solution supports Thailand's Climate Change Master Plan (2015–2050) by including carbon credit tracking and reporting features linked to national GHG accounting methods, enabling small and medium producers to participate in carbon markets while meeting sustainability targets. Together, these regulatory and technical considerations demonstrate how policy frameworks can guide agricultural innovation. The solution's design directly responds to these requirements, balancing certification, compliance, and user accessibility. These insights, along with stakeholder feedback, inform the next phase of research.

In addition, several technical documents reviewed, such as GS1 EPCIS 2.0 and CBV guidelines (GS1, 2021), define interoperability requirements that go beyond national frameworks. These stress the adoption of common identifier strategies (GTIN, GLN, lot/serial numbers) specified in the GS1 General Specifications (GS1, 2022b), standardized capture/query APIs, and schema governance to ensure cross-platform data exchange. Without these specifications, systems risk creating isolated, custom integrations. Likewise, scalability considerations appear in blockchain technical guidelines, including Hyperledger Fabric performance recommendations (Hyperledger Foundation, 2021) and Ethereum 2.0 specifications (Buterin et al., 2021), which recommend clear load assumptions, throughput targets, batching/partitioning methods, and cost transparency. These requirements shape the inclusion of scalability parameters as part of system design features.

4.2. Stakeholder insights

4.2.1. Demographic profiles

Table 4 presents the sample (N = 42) reflected diverse roles, ages, and income levels. It is balanced representation with 20 male and 20 female participants across all stakeholder groups. Predominantly, 20–40 years (85 % of participants: 19 between 20 and 30 years and 17 between 31 and 40 years), aligning with tech-adoption trends in Thai agribusiness. Only 6 participants were between 41 and 60 years old. Clear socioeconomic disparities emerged, with farmers earning ≤ 20,000 THB/month while developers and manufacturers earned ≤ 40,000 THB/month. Consumer incomes ranged up to 60,000 THB/month. The demographic result of 65 % held vocational certificates or bachelor's degrees, underscoring the need for user-friendly blockchain interfaces to accommodate varying technical literacy levels. The older demographic (41–60 years: 3 participants, 31–40 years: 2 participants, 20–30 years: 2 participants) with lower formal education levels (predominantly secondary education or vocational certificates) and the lowest income bracket (0–20,000 THB/month). Younger demographic (20–40 years) with higher education levels (vocational certificates to bachelor's degrees) and higher income levels.

Among the farmers (n = 10), there were 4 female and 6 male participants. The manufacturer group consisted of 2 male and 1 female participant, all aged 20–40 years with monthly incomes ranging from 0 to 40,000 THB. The logistics group had 2 males and 1 female, while all developers (n = 5) were 3 male and 2 female. The retailer group had 2 females and 1 male, and participants from the Thailand Greenhouse Gas Management Organization had 2 females and 1 male, all aged between 20 and 40 years old. The consumer group consisted of 7 female and 8 male participants, with ages distributed across all ranges (5 in 20–30, 4 in 31–40, and 3 in 41–60 years old). Snowball sampling effectively captured hidden networks (e.g., informal farmer-distributor relationships) that might not have been identified through purely purposive approaches, providing insights into organic supply chain dynamics. Potential bias toward tech-literate stakeholders was mitigated by including low-income farmers via agricultural cooperatives, ensuring representation of traditionally marginalized voices in technology adoption discussions.

4.3. Stakeholder interviews

A systematic thematic synthesis was conducted (see Table 5), integrating qualitative findings from stakeholder interviews. The interviews revealed behavioral patterns, desired outcomes, and key challenges that were coded, categorized, and compared across nine stakeholder groups.

- **Farmers** showed strong support for organic farming, focusing on sustainable pest control, natural fertilizers, and eco-friendly production. However, they needed simpler technologies to track crops, check soil health, and handle certifications. Challenges included limited digital skills, high costs, and poor access to traceability tools, highlighting the need for affordable, easy-to-use solutions with training.
- **Manufacturers** prioritized food safety and quality by following strict production rules and certifications like GMP and HACCP. They wanted carbon labels and better traceability to gain consumer trust

Table 4
Demographic profile of interviewees (n = 40).

Demographic variable	Category	Number of interviewees (Stakeholders)								
		farmers (n = 7)	Manufacturer (n = 3)	Logistics (n = 3)	Retailer (n = 3)	Developer (n = 5)	Participants from Thailand GHG (n = 3)	Participant from FDA (n = 3)	Participants from Organic certification agencies (n = 3)	Consumer (n = 12)
Gender	Male	3	2	2	1	3	1	2	1	5
	Female	4	1	1	2	2	2	1	2	7
Age(years)	20–30	2	2	2	1	2	2	2	1	5
	31–40	2	1	1	2	3	1	1	2	4
	41–60	3	-	-	-	-	-	-	-	3
Income (Baht)	0–20,000	4	1	1	2	2	2	1	2	7
	20,001–40,000	3	2	2	1	3	1	2	1	3
	40,001–60,000	-	-	-	-	-	-	-	-	2
	60,001–80,000	-	-	-	-	-	-	-	-	-
	80,001–100,000	-	-	-	-	-	-	-	-	-
	More than 100,000	-	-	-	-	-	-	-	-	-
Educational Level	Secondary education	4	-	-	-	-	-	-	-	2
	Vocational Certificate/ Diploma	3	1	2	1	-	-	2	1	3
	Bachelor	-	2	1	1	2	2	1	1	5
	Master	-	-	-	1	2	1	-	1	2
	PhD	-	-	-	-	1	-	-	-	-

but struggled with complex international certification processes. Many found blockchain technology hard to use, suggesting the need for a user-friendly system linked to existing certification bodies.

- **Logistics providers** relied on data for cold chain management, using QR codes and barcodes. Their main goal was real-time temperature and transport monitoring to protect product quality. Challenges included high maintenance costs, lack of training, and environmental risks during shipping. This indicated a need for IoT-based environmental tracking and easier operations.
- **Retailers** focused on improving stock management and freshness to satisfy customers. They wanted systems to track quality and make shopping easier but faced issues with spoilage, inaccurate stock counts, and expiration dates. This suggested a need for digital shelf-life monitoring.
- **Developers in academia** supported secure, user-friendly blockchain systems with easy access to product data. They worried about data security and compatibility with different systems, leading to a preference for permissioned blockchain that ensures both transparency and privacy.
- **Regulatory agencies** (such as Thailand's GHG Agency and FDA) emphasized accurate carbon data and digital systems for food safety compliance. They wanted more carbon footprint certifications and automated inspections but faced problems with inconsistent data, staff shortages, and varying standards. This called for standardized data tools, smart contracts, and inspection dashboards.
- **Organic certifiers** aimed to simplify inspections and farm checks through digital tools and better training. Their challenges included low supply chain transparency and incompatible certification systems, supporting blockchain-based audit trails and automated alerts.
- **Consumers** preferred trusted organic products with eco-labels but wanted more transparency about origins and production. High prices and difficulty verifying organic claims were concerns, suggesting a mobile app with QR code scanning to check product history and certifications.

After identifying themes across behaviors, desired outcomes, and pain points for each stakeholder group, the findings were systematically interpreted to determine the functional capabilities the system would require. This process involved translating qualitative statements, such as 'I wanted easy to use technology' or 'the certification process is too complicated,' into actionable system requirements. These requirements serve as the bridge between stakeholder expectations and system functionalities. Table 6 shows how raw qualitative data from interviews was linked to system requirements and then mapped to recommended technical features. Once these requirements were defined, they informed the formulation of recommended solutions tailored to each stakeholder group. Each solution corresponds directly to stakeholder needs and is designed to address specific operational challenges, ensuring that the proposed design is not only technically sound but also rooted in the real-world concerns and expectations of its intended users.

4.4. MVP architecture and three-layer platform

The MVP feature design was shaped through a triangulation of two key data sources stakeholder interviews and document analysis. While interviews identified user pain points and expectations, document analysis ensured that the features adhered to institutional standards and regulatory constraints. For instance, the need for a simple mobile interface for farmers was echoed both in interviews and in national agricultural policy promoting digital traceability by MOAC. Similarly, the smart certification dashboard responded to manufacturer demands for real-time certification and aligned with ACT organic standards and FDA inspection protocols. The use of a permissioned blockchain structure was supported by developers' concerns about data security and validated by the PDPA and ETDA blockchain compliance requirements. Table 7 summarizes how each feature is supported by both data sources.

Based on the integration of stakeholder interviews and document analysis, nine thematic requirements were synthesized into Minimum Viable Product (MVP) features. It is necessary to translate these findings into a practical system design. These features were then mapped onto a three-layer architecture Business Layer, IoT Traceability Layer, and Blockchain Layer. As recommended in design-oriented research, system architecture should directly reflect empirical insights to ensure real-world applicability. Fig. 3 shows the Architecture of the blockchain food traceability system. The following section presents the proposed three-layered blockchain traceability platform comprising the business, IoT, and blockchain layers developed in response to the identified requirements and constraints within Thailand's organic food supply

Table 5
Themes identified through in-depth interviews with stakeholders.

Stakeholder		Theme	Quotation
Farmer	Behaviors	Organic Farming for Sustainable Growth	“I grow vegetables using organic farming methods, controlling the contamination from chemicals.” (Farmer 1)“We focus on maintaining the natural balance of the ecosystem by using organic pest control methods, such as beneficial insects and natural repellents, to protect our crops without harmful chemicals.” (Farmer 4)“Our garden uses natural fertilizers and reduces the use of chemicals such as chemical fertilizers, pesticides, and herbicides.” (Farmer 7)
	Desired outcomes	Empowering Farmers with Technology for Sustainable and Organic Farming Practices	“I wanted easy-to-use technology that would help manage crop data and reduce errors in manual data recording.” (Farmer 5)“Need a system that helps organize crop data on the farm in an orderly manner so that production can be accurately tracked” (Farmer 2)“A system that helps manage the recording of planting data to apply for various standard certifications.I want a tool that helps me monitor soil health and moisture levels, so I can make better decisions for my crops.” (Farmer 3)
	Obstacles and Problems (Pain Points)	Complex, Costly, and Difficult-to-Access Technology Solutions	“It might be about the cost of purchasing new technology.” (Farmer 6)“I don’t have enough knowledge about how to use blockchain technology or other data storage systems.” (Farmer 1)“I don’t know what format is most appropriate to manage the data in.” (Farmer 3)
Manufacturer	Behaviors	Ensuring Quality and Safety through Rigorous Production Standards	“We control every step of production to ensure that the raw materials we use are of high quality and meet standards.” (Manufacturer 1)“Our factory has passed GMP and HACCP standards to prevent risks in the production process.” (Manufacturer 2)“We conduct food product analysis such as heavy metals and minerals, vitamins and nutritional values before delivery to customers.” (Manufacturer 3)
	Desired Outcomes	Achieving Environmental Certifications and Enhanced Traceability for Consumer Trust	“We want our products to be certified as environmentally friendly. Which will help build credibility.” (Manufacturer 1)“We are also interested in requesting a carbon footprint label for products in our factory.” (Manufacturer 2)“In fact, our company has a traceability system for raw materials to request a certificate, but it is not a system that allows consumers to check the origin of the food.” (Manufacturer 3)
	Obstacles and Problems (Pain Points)	Navigating Complex Certification Processes and Adopting New Technologies	“The verification process for various certifications is quite complicated.” (Manufacturer 1)“But I don’t know where to start because normally we only apply for organic certification in the United States, Europe and Japan.” (Manufacturer 2)“It’s very interesting, but I’m an old-school person. When I hear the word blockchain, I feel that it’s difficult.” (Manufacturer 3)
Logistics Provider	Behaviors	Ensuring Product Integrity through Data-Driven Transportation and Storage Management	“Our company transports food using refrigerated trucks and periodically checks the condition of the products.” (Logistics provider1)‘We have a system for storing data for retrospective inspection. You can see who edited the data or document.” (Logistics provider 2)“Warehouse and transportation management using barcodes and QR codes to track the status of goods.” (Logistics provider 3)
	Desired Outcomes	Real-Time Monitoring and Seamless Warehouse and Transportation Operations	“We want to develop a system that can control and monitor the temperature of products in real time so that customers and consumers can accurately track the

(continued on next page)

Table 5 (*continued*)

Stakeholder		Theme	Quotation
			condition of products throughout the transportation process." (Logistics provider 1)"To make the transportation process more accurate and transparent." (Logistics provider 2)"I want the warehouse management and transportation system to be smooth and error-free." (Logistics provider 3)
	Obstacles and Problems (Pain Points)	Challenges in Temperature Control, Shipping Delays, and System Maintenance Costs	"The challenge we face is maintaining the temperature of the product in all weather conditions and distances." (Logistics provider 1)"It could be a delay in shipping and inventory control in multiple warehouses." (Logistics provider 2)"The cost of maintaining the system and training employees to be knowledgeable in using the system." (Logistics provider 3)
Retailer	Behaviors	Optimized Inventory and Product Selection through Data-Driven Management	"We manage our inventory by category using a digital system for accurate purchasing and stock tracking." (Retailer 1)"We usually analyze customer purchasing behavior to make decisions about stock management." (Retailer 2)"There is a constant selection of high-quality and certified products." (Retailer 3)
	Desired Outcomes	Enhancing Customer Convenience and Ensuring Product Quality and Safety	"Because we want customers to buy products conveniently and reduce stock loss." (Retailer 1)"I prioritize providing products that meet customer needs and want customers to purchase quality and safe products." (Retailer 2)"To assure customers of the quality of products purchased from us."
	Obstacles and Problems (Pain Points)	Challenges in Stock Accuracy, Expiration, and Product Freshness	"Sometimes, a delay in stock updates can lead to out of stock or oversupply issues." (Retailer 1)"Some organic products expire before they are sold out." (Retailer 2)"The problem encountered is maintaining the freshness of food, which tends to spoil easily." (Retailer 3)
Developer/ Researcher	Behaviors	User-Centric Design and Secure Blockchain Systems	"I think that application development should focus on ease of use, not complicated, in terms of processes, menus, backgrounds, patterns." (Developer 3)"Our team focuses on designing blockchain systems that can safely support a large number of transactions." (Developer 2)
	Desired Outcomes	Simplicity and Convenience in Accessing Product Information via Technology	"We want users to be able to check the source of the product information quickly and conveniently." (Developer 1)"From my experience, I think the system needs to be easy to use because not everyone has the knowledge or expertise to use blockchain technology." (Developer 3)
	Obstacles and Problems (Pain Points)	Balancing Data Security and Integration Challenges in System Development	"It might be a matter of security and privacy of customer data." (Developer 1)"The main problem is that integrating data from different sources with different standards and structures can lead to errors or delays." (Developer 3)
Participants from Thailand GHG Agency	Behaviors	Comprehensive Monitoring and Collaboration for Carbon Footprint Management	"The NBTC is responsible for monitoring and assessing the carbon footprint of various products by collecting data from all production processes. Therefore, various types of certifications can be issued." (Participants from Thailand GHG Agency 2)"The NBTC works with government and private sectors on various projects to reduce greenhouse gases, providing advice and training to the public, communities, businesses and educational institutions." (Participants from Thailand GHG Agency 3)
	Desired Outcomes	Encouraging Participation in Carbon Footprint Certification for	"The NBTC is trying to encourage businesses to apply for carbon footprint labels, both

(*continued on next page*)

Table 5 (*continued*)

Stakeholder		Theme	Quotation
		Environmental Impact	for organizations and products.” (Participants from Thailand GHG Agency 1)“We would like businesses and industries to join the program or apply for certification to reduce greenhouse gas emissions and be aware of their environmental impact.” (Participants from Thailand GHG Agency 2)
	Obstacles and Problems (Pain Points)	Ensuring Accurate Data Recording for Carbon Assessment	“Creating knowledge and understanding for small and medium-sized entrepreneurs about submitting product carbon footprints.” (Participants from Thailand GHG Agency 3)“From my field visits to conduct assessments, I found that many business sectors lacked retrospective data recording regarding the production process.” (Participants from Thailand GHG Agency 2)
Participant from FDA	Behaviors	Leveraging Technology and Data for Regulatory Efficiency and Compliance	“I rely on tools like automation and data analysis to ensure safety while reducing review time.” (Participant from FDA 3)“I use software to keep records, track issues, and make sure everything meets the rules.” (Participant from FDA 1)“I focus on scientific data, health risks, and government regulations.” (Participant from FDA 2)
	Desired Outcomes	Enhanced Efficiency and Adaptability in Food Safety Oversight	“Adding more inspectors, using technology to track risks, and improving coordination between agencies.” (Participant from FDA 2)“By creating teams to study new food tech and updating rules quickly.” (Participant from FDA 3)“Better training, more staff, and advanced inspection tools systems.” (Participant from FDA 1)
	Obstacles and Problems (Pain Points)	Resource Constraints and Industry Diversity in Ensuring Comprehensive Food Safety Compliance.	“Different industries have different standards, and there aren’t enough inspectors to cover everything.” (Participant from FDA 2)“With fewer staff, we can’t inspect as often or in as much detail as we need to.” (Participant from FDA 1)“I look for ways to meet safety standards while supporting eco-friendly practices like reduced waste.” (Participant from FDA 3)
Participants from Organic certification agencies	Behaviors	Ensuring Compliance Through Inspections, Testing, and Standards Review	“I review documents, visit the site, and test samples to ensure everything follows organic rules.” (Participants from Organic certification agencies 1)“By checking records, inspecting farms, and testing products for prohibited chemicals.” (Participants from Organic certification agencies 2)“Once a year or as needed to match new standards.” (Participants from Organic certification agencies 3)
	Desired Outcomes	Streamlining Processes and Enhancing Capabilities for Future-Ready Organic Certification	“Simplify paperwork, use digital tools, and offer more training for inspectors.” (Participants from Organic certification agencies 2)“They’ll include more sustainability practices and adapt to climate change challenges.” (Participants from Organic certification agencies 1)“More training on new farming methods and better tools to test products.” (Participants from Organic certification agencies 3)
	Obstacles and Problems (Pain Points)	Challenges in Supply Chain Transparency and Resource Management for Organic Certification.	“It’s hard to track every step, especially when suppliers don’t provide enough data.” (Participants from Organic certification agencies 1)“Different rules in different countries and lack of staff to check everything.” (Participants from Organic certification agencies 2)“I check how farms use water, manage waste, and conserve resources.” (Participants from Organic certification agencies 3)

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Table 5 (*continued*)

Stakeholder		Theme	Quotation
Consumer	Behaviors	Conscious Consumption of Organic Products for Health, Trust, and Sustainability	“I usually buy organic products regularly, whether it's vegetables, fruits or organic brown rice.” (Consumer 1)“I choose to buy products with organic certification labels that are sold in reliable stores.” (Consumer 9)“My brother buys organic products because he thinks they are safe and free of toxic residues, since he is sick and old.” (Consumer 6)
	Desired Outcomes	Transparency, Ethical Sourcing, and Accessibility in Organic Product Information	“If possible, I would like to know where the products come from.” (Consumer 2)“I would like to know more about the production process and planting methods of the products I purchased.” (Consumer 9)“I think you want to know the source of the food, whether it's vegetables, fruits or meat, such as which farm, which province, and whether it passes the standards.” (Consumer 12)
	Obstacles and Problems (Pain Points)	Challenges in Verifying Authenticity, Affordability, and Availability of Organic Products	“I think finding information about the manufacturing process of some products is not very clear.” (Consumer 5)“Sometimes products with organic labels are still very expensive and it is not possible to verify the information on the label to verify whether it is actually certified or not.” (Consumer 3)“Organic products are often more expensive than conventional ones, making it hard to afford them regularly.” (Consumer 7)

chains. This integration ensures each feature directly supports traceability, transparency, and regulatory compliance, while remaining usable and accessible across all supply chain actors.

The Business Layer captures stakeholder interactions such as farming, retail, and consumer behaviors. The business layer in the supply chain includes processes related to the manufacturing and distribution of food products, covering the journey from producers to consumers. To streamline the overall supply chain operations, food supply chain activities are classified into three primary stages: production (manufacturing), distribution (transportation), and consumption (retail) (Sadraei et al., 2023). In this study, stakeholders emphasized operational inefficiencies, particularly among farmers and

Table 6
Interview themes mapped to system requirements and solution feature enhancements.

Interview theme	System requirements	Recommended feature enhancements
Sustainable Organic Farming & Technology Adoption	Easy-to-use, low-cost digital tools for crop data, certification, and soil/ moisture monitoring	Easy to use mobile app and soil/moisture IoT support features.
Production Standards, Certification, and Traceability	Blockchain-integrated traceability and certification system with carbon labeling	Certificates verify function for standard support and carbon label tracking features.
Cold Chain Management & Data-Driven Logistics	Real-time temperature and logistics monitoring with QR/barcode integration	IoT integration for temperature, GPS tracking, and QR-code syncing
Inventory Optimization & Product Quality	System for stock freshness, expiration tracking, and digital inventory updates	Add a system that shows which products will expire first and how fresh they are
User-Friendly and Secure Blockchain Design	Simple UI/UX with secure blockchain backend and quick access to product data	User friendly interface
Carbon Footprint Monitoring and Capacity Building	Accurate, retrospective carbon tracking and education tools for SMEs	Carbon audit-ready export functions
Regulatory Efficiency and Food Safety Compliance	Automated risk tracking, data tools for oversight, and streamlined inspection systems	Smart contract inspection workflows and digital audit trails
Transparent Organic Certification and Inspection	Digital certification dashboard, sustainability metrics, and staff training systems	Inspector login module and automated alerting system
Ethical, Transparent, and Accessible Consumption	Transparent product origin info via QR, affordability, and verified organic claims	Consumer-facing mobile app for product history, price insights, and eco-labels

manufacturers. As per Table 5, farmers cited high costs and technological complexity as barriers:

> "It might be about the cost of purchasing new technology." (Farmer 6)

> "I don't have enough knowledge about how to use blockchain technology." (Farmer 1)

This business layer integrates low-cost onboarding tools to address this and automated documentation via smart contracts, reducing reliance on manual processes.

Manufacturers struggled with certification transparency such as

> "The verification process for certifications is complicated." (Manufacturer 1)

As per Figure 3, the Business Layer enables seamless data sharing with regulators and auditors. For these sustainability practices to be effectively conveyed throughout the supply chain, active participation from all stakeholders, including organic farmers, vegetable and fruit producers, distributors, retailers, logistics providers, government agencies, certifying bodies, and consumers, is essential. These stakeholders must back their sustainability claims with verifiable evidence. Information regarding sustainability efforts, such as sustainable agricultural practices, fair labor conditions, and carbon footprint metrics, should be tracked and documented throughout the production-distribution-consumption cycle: from producing and processing items to receiving, dispatching, selling, and purchasing them. Effective coordination and collaboration among stakeholders are crucial to meeting customer expectations and ensuring that sustainability commitments are clearly communicated across the supply chain.

The IoT Traceability Layer encompasses user interfaces designed to enable supply chain stakeholders and machines (such as IoT sensors and

Table 7
Integration of document and interview themes into MVP design.

Integrated theme	System requirements	MVP features	Mapped architecture layer(s)	Rationale for layer mapping
Digital Tools for Organic Farming	Affordable and easy-to-use digital tools for planting, fertilization, and soil/moisture monitoring	Mobile app + IoT sensors for crop and soil tracking	**IoT Layer + Business Layer**	Mobile app interfaces (Business Layer) collect real-time soil/moisture data from IoT sensors (IoT Layer) enabling farmers to manage field operations efficiently.
Certification and Traceability Compliance	Blockchain-based end-to-end traceability with verifiable and auditable certification aligned with ACT and IFOAM	Certification dashboard + blockchain smart contracts + carbon label logs	**Blockchain Layer + Business Layer**	Certification dashboards (Business Layer) interact with blockchain smart contracts (Blockchain Layer) ensuring immutable traceability and compliance with ACT and IFOAM standards.
Cold Chain and Logistics Monitoring	Real-time transport monitoring (temperature, oxygen, GPS); QR/barcode integration	IoT-based logistics module with real-time GPS and temperature + QR sync	**IoT Layer + Blockchain Layer + Business Layer**	IoT devices (IoT Layer) monitor real-time conditions, data is synced and stored on blockchain (Blockchain Layer), with logistics management tools for users (Business Layer).
Inventory Accuracy and Product Freshness	Shelf-life tracking, spoilage alerts, expiration updates	Retailer system for digital freshness and stock alerts	**IoT Layer + Business Layer**	Shelf-life and freshness monitoring are driven by inventory systems (Business Layer) with IoT-enabled spoilage and stock tracking features (IoT Layer).
Secure and User-Friendly Blockchain Interface	UI simplicity + secure permissioned blockchain with PDPA/ETDA compliance	Intuitive UI + permissioned blockchain + encryption + digital signatures	**Blockchain Layer + Business Layer**	Secure backend with permissioned blockchain and encryption (Blockchain Layer), while ensuring a simple user interface for ease of use (Business Layer).
Carbon Footprint Monitoring and Reporting	Blockchain-linked GHG calculator, audit dashboard, and national policy-aligned reporting	Blockchain-integrated carbon calculator + audit export tools + carbon credit tracker	**Blockchain Layer + Business Layer + IoT Layer**	IoT sensors collect carbon emission data (IoT Layer), calculations are logged and verified on blockchain (Blockchain Layer), with user-facing dashboards for reporting (Business Layer).
Food Safety and Smart Regulation	Digital audit trails, automated inspection logs, smart contract verification	QR-coded digital audit logging + smart contract-based inspection workflows	**Blockchain Layer + Business Layer + IoT Layer**	Smart contract-enabled inspections (Blockchain Layer) integrate with QR-coded audit trails (IoT Layer), providing real-time compliance tracking interfaces (Business Layer).
Transparent Organic Certification and Inspection	Real-time inspector access, auto-alerting, dashboard access for agencies	Inspector portal + alert system + real-time compliance logs	**Blockchain Layer + Business Layer**	Inspector portals and compliance logs (Business Layer) access blockchain-stored certification records (Blockchain Layer) to enhance transparency.
Ethical Consumption and Product Origin Transparency	QR-based product trace, certified origin access, eco-label and price insight	Consumer mobile app with QR scanning + price + eco-label validation	**Blockchain Layer + Business Layer + IoT Layer**	Consumers use mobile apps (Business Layer) to scan QR codes (IoT Layer) that retrieve immutable product origin data from blockchain records (Blockchain Layer), validating eco-labels and pricing.

RFID) to easily capture and store sustainability-related information within a distributed network. Authorities and third-party auditing and certification bodies can also use these interfaces to validate and audit claims made by supply chain participants. The user interface module can include web and mobile apps, offering easy interaction for registering, updating, verifying, and auditing the sustainability attributes of food products. These interfaces display information such as product origin, sustainable production methods, certifications, carbon footprint, and other sustainability metrics. Additionally, interactive features, like product scanning via QR codes or barcodes, allow consumers convenient access to real-time information about a product's sustainability attributes. This design ensures seamless integration between physical products and traceable digital sustainability information at each stage of the supply chain, facilitating the collection and dissemination of sustainability data. In this study, logistics providers and retailers highlighted the need for real-time data to mitigate risks. Logistics providers demanded temperature and condition monitoring that

> "We want to develop a system to control product temperature in real time." (Logistics Provider 1)

The IoT Layer supports data collection from the field such as soil moisture or cold-chain temperature. The IoT layer deploys sensors and RFID tags to track environmental conditions, directly addressing this need. Retailers faced stock inaccuracies.

"Delays in stock updates lead to oversupply." (Retailer 1). IoT-enabled inventory automation in the MVP minimizes such errors by syncing supply chain data across nodes. The Internet of Things (IoT) traceability layer plays a critical role in enhancing transparency, accountability, and sustainability across various industries, particularly in the food sector. This layer combines IoT devices with blockchain technology to create a comprehensive traceability system capable of monitoring products throughout their entire lifecycle from production to consumption. It includes diverse IoT devices, such as sensors (for temperature, humidity, and GPS) and identification tools (like RFID and QR codes). These devices continuously collect and transmit data on environmental conditions and product status to the upper layers of the system. Acting as an intermediary between IoT devices and blockchain, this layer handles device authentication, data transmission, and the integration of smart contracts, ensuring that the data collected is correctly processed and stored.

All transactions are recorded on a public ledger, making it easier to verify claims about product origins and handling methods for consumers and regulators. Automated data collection reduces human error and speeds up processes like inventory management and compliance reporting. Consumers are more likely to trust brands that provide accurate information about their products' journey from farm to table, enhancing brand loyalty and competitiveness. By enabling comprehensive tracking of items throughout their lifecycle, the IoT traceability layer is essential for raising sustainability standards across multiple industries. The incorporation of blockchain technology boosts efficiency and transparency while building consumer confidence in food safety and sustainability initiatives.

The Blockchain Layer ensures tamper-proof traceability, certification logging, carbon audit trails, and secure inspection workflows. The blockchain layer serves as the core technological infrastructure that ensures tamper-proof data for sustainability verification and validation within a decentralized and distributed network. It plays a crucial role in maintaining the accountability of sustainability communication

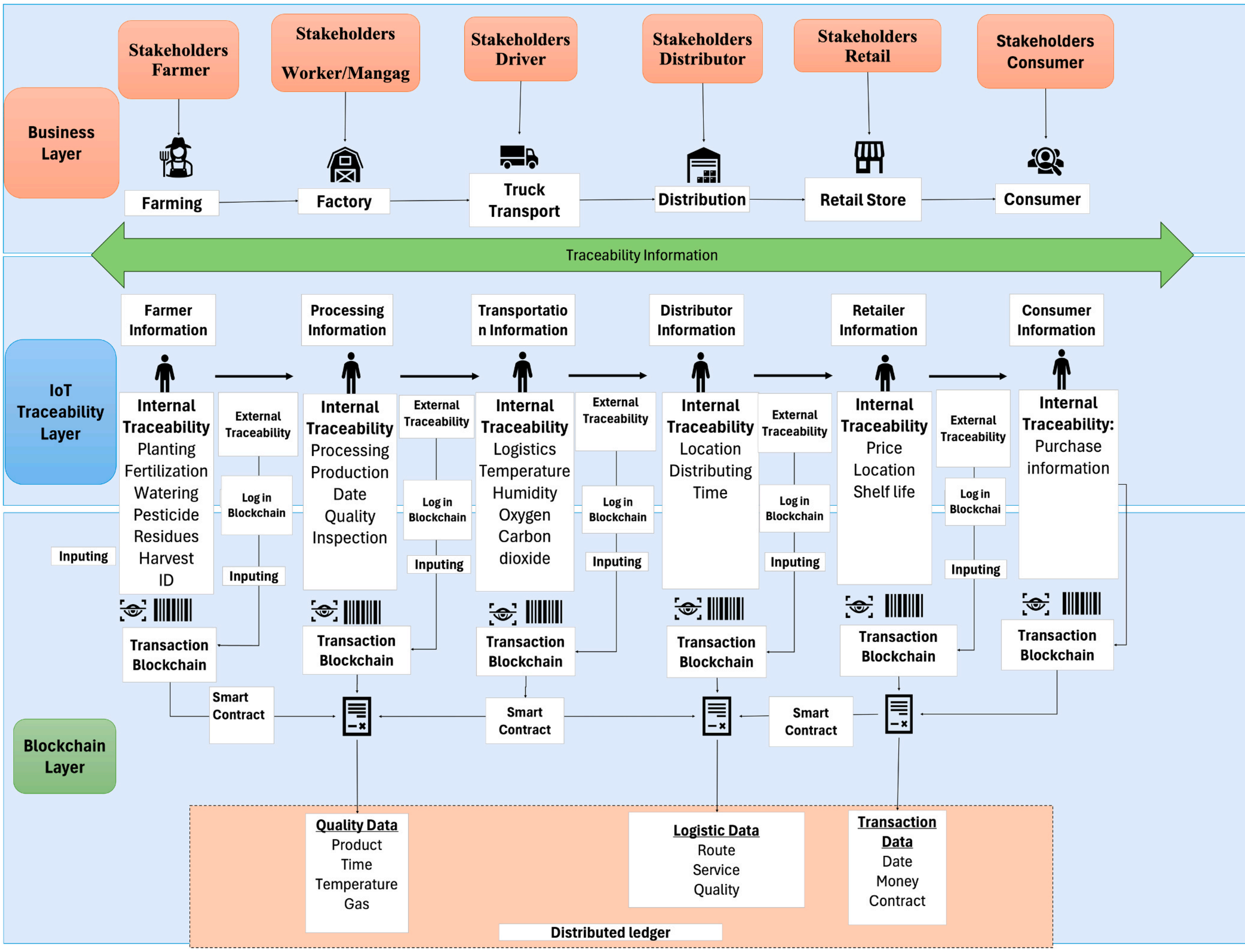

Fig. 3. Architecture of blockchain food traceability system.

throughout the supply chain by utilizing a consensus system, data authentication mechanisms, and a distributed ledger. These components, based on specified data schemas, ensure the reliable and precise maintenance of sustainability-related data, certificates, and labels. The blockchain layer immutably records product journeys, allowing consumers to scan QR codes for verified origins.

Consumers and regulators prioritized data integrity and transparency.

Consumers sought proof of authenticity "I want to know the source of the food." (Consumer 12)

Certification agencies noted regulatory hurdles "Different rules in different countries complicate compliance." (Organic Certification Agency 2)

The MVP's modular design accommodates regional standards, with validator nodes ensuring localized compliance. The consensus method is established through the coordination of member nodes and validator nodes within the blockchain network. Member nodes include key participants in the supply chain, such as producers, manufacturers, distributors, and retailers, while validator nodes consist of regulatory agencies and independent auditing and certification bodies. Both member and validator nodes adhere to standardized sustainability indicators, ensuring that data storage is both safe and cost-effective. Validator nodes are responsible for ensuring that the metrics and traceable units defined in the traceability layer are accurately recorded and updated within the blockchain, using the user interfaces described in the application layer to integrate standardized information into the system.

The data authentication mechanism guarantees the integrity of sustainability data, ensuring that it originates from verified sources, including digital twins and external oracles.

The distributed ledger, which employs specialized data standards such as timestamps, block data, and hash cryptography, securely records and stores sustainability data in a nearly real-time accessible format. This system provides authenticated, chronological, and immutable records of the sustainability attributes of food products. By doing so, it enhances collaboration across the supply chain through the precise monitoring of the timing and location of each supply chain activity. Furthermore, it empowers consumers by providing them with verified, accessible data, enabling them to make more informed and sustainable purchasing decisions.

4.5. Interoperability by design: forging a connected organic food ecosystem

While the critical need for interoperability was consistently highlighted throughout our stakeholder interviews and document analysis, merely acknowledging it is insufficient. For the MVP architecture to achieve true system-level credibility and facilitate seamless data exchange, interoperability must be explicitly engineered into its very foundation. Our proposed solution rigorously operationalizes this principle through a strategic alignment with established international traceability standards, a robust identifier strategy, clear capture and query specifications, and transparent schema governance mechanisms.

This meticulous design ensures that participants across Thailand's organic food supply chain are not constrained by bespoke, custom-built integrations. Instead, they can actively engage in a cohesive, shared digital ecosystem that is fully consistent with both Thailand's national Carbon Footprint for Products initiative and the European Union's emerging Digital Product Passport.

At the heart of this design, the MVP adopts GS1 EPCIS 2.0 and the Core Business Vocabulary as the foundational backbone for all event data exchange. This critical choice guarantees that our capture and query interfaces adhere to globally recognized conventions, enabling the transparent and standardized recording of essential events throughout the supply chain, including production, processing, and logistics. This encompasses event types such as ObjectEvent (tracking specific items), AggregationEvent (grouping items), TransformationEvent (changes to items, e.g., processing), and TransactionEvent (business transactions). To further harmonize data across the diverse array of actors in the supply chain, the system consistently applies universal GS1 identifiers: GTIN for product identification, GLN for precise location identification (e.g., farms, factories, warehouses), and lot/serial numbers for granular tracking at both batch and individual item levels. This comprehensive approach is vital for reliably linking carbon footprint data to specific production lots and distinct shipment events, ensuring unprecedented accuracy and auditability.

To facilitate dynamic data exchange, RESTful APIs are implemented, meticulously aligned with EPCIS capture and query specifications. These APIs support both on-chain and off-chain data flows, ensuring flexibility and efficiency. Crucially, they incorporate role-based access and permissioned querying capabilities, allowing authorized entities such as regulators, certification bodies, and SMEs to securely capture or request relevant CFP/DPP data in a standardized, machine-readable format.

To actively counteract fragmentation and ensure systemic cohesion, schema updates are managed through a lightweight yet effective governance mechanism. This mechanism is strategically anchored in two pivotal Thai institutions: the Greenhouse Gas Management Organization and Organic Agriculture Certification Thailand. This ensures that all changes to data schemas undergo careful version control, guaranteeing that all participating actors consistently operate on validated schemas while maintaining essential backward compatibility.

Finally, a key aspect of this interoperability strategy is the explicit mapping of EPCIS event attributes to the specific requirements of both CFP (e.g., emission factors, activity data, reporting templates) and DPP (e.g., lifecycle stage, material composition, carbon footprint). This direct mapping capability enables dual compliance with both national and international reporting frameworks, streamlining regulatory processes and strengthening global market access for Thailand's organic food products. The detailed conformance plan for this "interoperability by design" is further illustrated in Table 8.

Table 8
Conformance plan for interoperability by design.

Standard / requirement	Implementation mechanism	Validation method
GS1 EPCIS 2.0 + CBV	Event modeling using Object, Aggregation, Transformation, and Transaction events	Smart contract validation of EPCIS event structure
Identifier Strategy (GTIN, GLN, Lot/ Serial)	Unique identifiers embedded in IoT and QR capture workflows	Cross-check against GS1 registry and smart contract rules
Capture / Query APIs	RESTful APIs aligned with EPCIS capture/query interface	API conformance testing with regulator & SME pilots
Schema Versioning & Governance	Version-controlled JSON schemas managed by TGO/ACT consortium	Regular schema audits and backward compatibility checks
Mapping to CFP/ DPP	Emission factors, activity data, lifecycle stage embedded in EPCIS event extensions	CFP/DPP compliance audits with TGO and EU alignment

5. Discussion

5.1. General discussion

The integration of regulatory analysis and stakeholder narratives (Table 7) reveals that blockchain-enabled carbon footprint traceability in Thailand's organic food sector is not merely a technological upgrade but a socio-technical reconfiguration that requires careful negotiation across institutional, environmental, and social domains. This aligns with Actor-Network Theory's (ANT) proposition that innovations emerge from heterogeneous networks of human and non-human actants whose relationships must be continuously translated and stabilized (Callon, 1986; Latour, 2005). For example, farmers' expressed need for "easy--to-use" tools directly shaped the design of IoT-based soil and crop monitoring systems, while regulatory texts such as the PDPA (2019) and TGO GHG Methodology (2023) became embedded within permissioned blockchain protocols, transforming policy into an active agent in the network (Duan et al., 2024).

Most prior blockchain traceability systems share three patterns: (i) ledger-centric designs that neglect regulatory standards, (ii) technology-isolated models without MRV or carbon accounting, and (iii) pilot-scale prototypes with limited SME adoption and policy alignment. Our architecture addresses these gaps,regulator-grade interoperability by embedding GS1 EPCIS 2.0 and EU DPP, integrated MRV design with carbon inventories, provenance versioning, and smart contract audits. Participatory scalability, co-created under the 5HI framework with SMEs, regulators, and consumers, supported by tiered service models and off-chain storage. Benefits include reduced certification fraud, lower SME adoption barriers, and CFP reporting aligned with Thailand's TGO standards. Pilot deployments will test throughput, audit readiness, and adoption outcomes.

Critically, the literature often treats blockchain adoption as a largely linear process of technical deployment (Lei et al., 2022), underplaying how socio-political contexts, institutional legitimacy, and ecological imperatives co-determine system design. By applying ANT, this study surfaces the "obligatory passage points" (Latour, 2005) that condition innovation, such as certification bodies (ACT, IFOAM) and government climate strategies, which do not passively support blockchain but actively shape its governance logic. In doing so, it addresses a gap in existing blockchain traceability studies that under-theorize the performative role of regulation in legitimizing and sustaining digital food systems (Gallo et al., 2021). Furthermore, the co-design approach adopted here embodies the principles of open innovation, where knowledge flows across organizational and sectoral boundaries enable faster problem-solving and more adaptive solutions (Sá et al., 2023; Majchrzak et al., 2023). By involving diverse actors early are farmers, regulators, IT developers, logistics firms, and consumer groups, the design process not only drew from a wider knowledge base but also built legitimacy and trust, critical to adoption in settings with varied digital literacy.

From a Quintuple Helix Innovation (5HI) perspective, the mapping of solution features to architecture layers such as IoT, Blockchain, and Business, operationalizes how environmental and societal objectives are engineered into the system (Borrero and Yousafzai, 2024). Each helix played a distinct role:

- **Academia** provided methodological rigor, ensuring that design decisions were grounded in both technical feasibility and prior empirical studies (Lopes et al., 2021).
- **Industries**, including processors, logistics firms, and retailers, contributed operational insights that shaped modules for cold chain monitoring and inventory management (Mayho et al., 2024).
- **Government** influence was evident in the integration of PDPA-compliant data controls and ETDA blockchain standards, embedding legal compliance into the system's core functions.

- **Civil Society** input, particularly from farmers and consumers, drove interface simplicity, trust-building measures, and eco-label transparency (Stephens, 2025; Starkbaum et al., 2024).
- **Natural Environment** was not simply a "target" of sustainability goals but an active design driver, informing the inclusion of IoT-linked carbon calculators aligned with TGO methodologies (Van Bueren et al., 2025).

This direct coupling of environmental indicators with blockchain verification challenges earlier 3HI and 4HI approaches, which tend to foreground economic and technological innovation over ecological integration. While prior work in blockchain food traceability often acknowledges environmental sustainability, it rarely demonstrates how ecological priorities can be technically instantiated at the architectural level. Here, the three-layer design logic, IoT for environmental sensing, Blockchain for immutable verification, and Business Layer for multi-actor usability, creates a replicable blueprint for embedding eco-social objectives into digital infrastructures.

However, the findings also point to tensions. While blockchain's decentralization is frequently lauded for enhancing trust (Feng et al., 2020; Kshetri, 2021), in practice, the permissioned architecture required by PDPA compliance centralizes certain governance functions, raising questions about how "distributed" authority truly is. Similarly, IoT integration enhances real-time monitoring but introduces interoperability and maintenance challenges for SMEs with limited technical capacity. These tensions underscore ANT's insight that stability in innovation networks is provisional; alignments must be continually renegotiated as technologies, institutions, and environmental conditions evolve (Astill et al., 2019).

By combining ANT's focus on actor translation with 5HI's holistic innovation framing, and grounding the process in open innovation principles, this study advances blockchain literature in two ways. First, it shifts the analytical lens from blockchain as a static "tool" to blockchain as an evolving governance infrastructure embedded in ecological, regulatory, and social systems. Second, it demonstrates that environmental integration in digital agriculture is not merely a normative aspiration but a technical reality when sustainability objectives are explicitly mapped to system layers. This contribution addresses calls for more inclusive, environmentally attuned models of digital innovation in agriculture (Michaelidou and Hassan, 2008; Gallo et al., 2021), offering both a conceptual framework and a practical design pathway for future eco-social blockchain applications.

5.1.1. Dominant patterns and architectural advancements

The findings of this study reveal that blockchain-based carbon footprint traceability in Thailand's organic food sector must move beyond the dominant patterns observed in earlier systems. As noted by Saberi et al. (2019b) and Kayikci et al. (2022), many prior architectures adopt ledger-centric designs that emphasize immutability but lack regulatory interoperability, limiting their relevance in policy-sensitive contexts. Kouhizadeh et al. (2021) and Wang et al. (2023) further highlight the prevalence of technology-isolated models that fail to integrate Measurement, Reporting, and Verification (MRV) protocols or carbon accounting mechanisms, critical components for credible sustainability reporting. Additionally, Erol et al. (2020) and Friedman and Ormiston (2022b) observe that most implementations remain at pilot scale, with limited SME adoption and weak alignment with national policy instruments.

This study addresses these limitations through a Minimum Viable Product (MVP) that integrates regulatory, ecological, and participatory dimensions. Unlike technology-first pilots (Bumblauskas et al., 2020; Lei et al., 2022), our architecture embeds Thailand's Personal Data Protection Act (PDPA, 2019) and the TGO GHG Methodology (2023) within permissioned blockchain protocols, transforming legal frameworks into active governance mechanisms. It links IoT-based carbon calculators to GS1 EPCIS 2.0 and the EU Digital Product Passport, ensuring traceability and verification standards are met. Co-design with farmers, regulators, logistics actors, and consumers, guided by the Quintuple Helix Innovation framework (Borrero and Yousafzai, 2024), builds legitimacy and usability, particularly for SMEs. This participatory approach reflects Actor-Network Theory's view that innovation emerges from negotiated relationships among human and non-human actants (Callon, 1986; Latour, 2005), a dynamic often underplayed in blockchain-CFP studies (Gallo et al., 2021).

The architecture delivers tangible benefits aligned with both regulatory and operational goals. It reduces certification fraud through immutable verification, lowers adoption barriers via tiered service models and off-chain storage, and enables carbon footprint reporting compatible with Thailand's TGO standards. These outcomes will be tested through pilot deployments that evaluate system throughput, audit readiness, and adoption metrics across diverse stakeholder groups. By embedding regulation, integrating ecological metrics, and operationalizing participatory governance, the MVP reframes blockchain as a socio-technical infrastructure, one that responds to the institutional, environmental, and social complexities of Thailand's organic food sector.

5.2. Research, managerial, and policy implications

This study advances theoretical discourse at the intersection of blockchain traceability, open innovation, and socio-technical adoption frameworks within Thailand's organic food supply chain. By integrating the Quintuple Helix Innovation (5HI) model with Actor-Network Theory (ANT) and open innovation principles, it reframes blockchain-enabled traceability as an eco-social innovation process rather than a purely technical intervention (Borrero and Yousafzai, 2024; Gallo et al., 2021). The 5HI perspective broadens ANT's socio-technical lens (Callon, 1986; Latour, 2005) by embedding the natural environment alongside academia, industry, government, and civil society, ensuring that ecological imperatives, such as carbon footprint tracking, are integrated from the outset.

5.2.1. Research implications

The study contributes to theory by positioning blockchain traceability as part of a broader sustainability-oriented innovation ecosystem. While prior research has emphasized blockchain's role in enhancing transparency, data integrity, and certification authenticity in agri-food systems (Feng et al., 2020; Menon and Jain, 2024), these discussions often address technical scalability, interoperability, and governance in isolation from behavioral and institutional contexts (Lei et al., 2022). By incorporating the 5HI model, this study demonstrates how ecological concerns and socio-institutional dynamics can be jointly embedded into digital adoption frameworks.

Theoretically, this integration extends blockchain adoption models by showing how multi-helix co-creation generates adaptive pathways for innovation, particularly in SME-dominated sectors. It also introduces a transferable framework for ASEAN-wide harmonization of traceability protocols across strategic commodities such as rice, seafood, and palm oil. Future research should test these findings empirically by developing metrics for evaluating multi-helix collaboration, conducting longitudinal studies to assess adoption outcomes, and comparing cases across ASEAN to examine scalability and policy transferability.

5.2.2. Managerial implications and policy implications

For managers and practitioners in Thailand's organic sector, the study highlights practical strategies for overcoming adoption barriers. A modular, permissioned blockchain architecture, combined with mobile-based data logging and user-friendly certification dashboards, offers SMEs a low-barrier entry into digital traceability systems (Lei et al., 2022). The findings emphasize that open innovation principles, such as iterative system design based on stakeholder feedback, are critical for building trust and ensuring long-term usability.

Certification bodies and supply chain managers can leverage smart contract-enabled workflows to reduce administrative overheads, streamline compliance audits, and improve data accuracy (Xu et al., 2023; Patro et al., 2025). At the consumer interface, QR code-enabled traceability tools enhance transparency regarding product authenticity, origin, and environmental credentials, thereby strengthening consumer trust and enabling firms to capture value through ethical consumption trends (Majchrzak et al., 2023). For managers, these insights point to clear adoption goals: integrating blockchain solutions that reduce compliance costs, enhance certification credibility, and strengthen consumer-brand relationships. Such measures can help SMEs achieve measurable improvements in operational efficiency and market competitiveness within three to five years.

From a policy perspective, the study underscores the importance of creating regulatory frameworks that embed ecological sustainability and cross-sector collaboration into digital governance. Policymakers should prioritize the establishment of digital certification standards and carbon footprint reporting mechanisms that align with the 5HI framework, ensuring that ecological imperatives are systematically integrated into agricultural governance. Thailand's regulatory trajectory offers opportunities to harmonize with ASEAN-wide digital integration strategies, enabling standardized traceability protocols and regional carbon credit mechanisms that incentivize SME participation. Cross-agency data interoperability is particularly critical for reducing duplication and ensuring efficient oversight. Policymakers should also consider targeted incentives, such as tax reliefs, subsidies for digital infrastructure, or preferential market access, for SMEs that adopt blockchain-enabled traceability systems.

Concrete policy targets include the introduction of national blockchain traceability guidelines within the next three years, the integration of carbon reporting into organic certification protocols by 2027, and the development of ASEAN-wide traceability harmonization for selected commodities by 2028. Collectively, these measures can position Thailand not only as a regional leader in digital sustainability governance but also as a credible player in high-value global export markets.

5.3. Limitations and future research

While this study conceptualizes a blockchain-based carbon footprint traceability system for Thailand's organic food supply chain, its scope is intentionally limited to early-stage design and feasibility assessment, providing a foundation for stakeholder co-creation without extending into prototype deployment or laboratory validation. The next phase should develop and test a functional prototype under real-world conditions (Technology Readiness Level 5) to assess performance, usability, and scalability, enabling stakeholders to refine system features through direct interaction. In the wider ASEAN context, comparative studies examining differences in regulations, market dynamics, and technological infrastructure could determine regional adaptability and support harmonized traceability standards for sustainable trade. Advancing to prototype implementation, engaging technology partners, and conducting cross-country analyses will help confirm the system's practicality and strengthen its role in fostering sustainable supply chains across Southeast Asia.

6. Conclusion

This study makes a significant contribution to the literature by proposing a blockchain-based carbon footprint traceability framework specifically designed for Thailand's organic food supply chain. Rather than presenting abstract technological potential, the research operationalizes the Quintuple Helix Innovation (5HI) model through a Minimum Viable Product (MVP), demonstrating how technical feasibility can be integrated with environmental accountability and institutional responsiveness. Drawing on Actor-Network Theory and open innovation principles, the framework offers a replicable model for sustainable digital transformation in agri-food systems. The architecture comprises three interdependent layers that reflect stakeholder needs and regulatory requirements. The business layer facilitates multi-stakeholder engagement from farming to consumption by incorporating low-cost onboarding tools and smart contract-based documentation. This directly addresses challenges faced by farmers, such as high technology costs and complexity, and by manufacturers, such as burdensome certification processes. The IoT traceability layer enhances transparency and risk mitigation through real-time data collection using sensors and RFID devices. It supports critical functions such as soil moisture monitoring, cold-chain logistics, and inventory accuracy, ensuring that physical products are linked to verifiable digital sustainability records. The blockchain layer serves as the core infrastructure for tamper-proof data integrity, providing immutable records for product provenance, certification logs, carbon audit trails, and secure inspection workflows. This layer meets consumer demands for authenticity and origin transparency while complying with regional data protection regulations through a permissioned blockchain model. The holistic integration of these layers ensures environmental sensing, regulatory compliance, and user-friendly design, fostering trust and legitimacy among stakeholders with varying levels of digital literacy. The framework improves traceability accuracy, supports alignment with national standards, and promotes ecological accountability through IoT-linked carbon calculators based on methodologies from the Thailand Greenhouse Gas Management Organization. Despite these advancements, the study acknowledges its limitations. The scope was confined to early-stage design and feasibility assessment, without full prototype deployment or laboratory validation. Moreover, while blockchain technology promotes decentralization, the need for a permissioned architecture to comply with data protection laws introduces a degree of centralized governance, raising questions about the distribution of authority. The proposed design developed through multi-stakeholder collaboration offers a realistic and adaptable blueprint for enhancing transparency, strengthening trust, and aligning with regional sustainability goals. The integration of IoT also presents interoperability and maintenance challenges, particularly for small and medium-sized enterprises with limited technical capacity. Based on these findings, the study proposes several concrete and testable directions for future research and development. These include developing and testing a functional prototype within selected organic cooperatives, conducting longitudinal audits to evaluate regulatory compliance, assessing the environmental impact through carbon reduction benchmarks, performing cross-country feasibility studies across ASEAN nations to explore regional adaptability, and engaging technology partners to address SME-specific challenges through cost-effective and user-friendly solutions. These steps will not only validate the system's practical utility but also strengthen its role in fostering sustainable, transparent, and inclusive supply chains across Southeast Asia.

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Ethical statement

The Ethics Committee for Human Research at Khon Kaen University reviewed our research protocols. The protocols were approved as an exemption, given the number HE673159.

CRediT authorship contribution statement

Chidozie Umeh: Conceptualization. **Teerapong Pienwisetkaew:** Data curation. **Sasichakorn Wongsaichia:** Data curation. **Chan Soea Aye:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Chavis Ketkaew:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Emilia Vann Yaroson:** Conceptualization.

Conflict of interests

The authors of this research study declare that there are no conflicts of interest.

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Appendix A. : Interview questions for stakeholders of processed food

A1. Farmers

Section 1. Demographic questions for organic farmers.

1. Gender

- Male
- Female

2. Age

- 20–30
- 31–40
- 41–60

3. Income (Baht)

- 0–20,000
- 20,001–40,000
- 40,001–60,000
- 60,001–80,000
- 80,001–100,000
- More than 100,000

4. Education Level

- Secondary education
- Vocational Certificate/ Diploma
- Bachelor
- Master
- PhD

5. Type of Farming

- Fruit Farming
- Vegetable Farming
- Mixed Fruit and Vegetables Farming

6. Years of farming experience

- 1 – 10
- 10 – 20
- 20 and above

Section 2. Behavior

- What types of fruits and vegetables do you grow, and how did you choose them?
- How are you planting and harvesting fruits and vegetables? Please explain the process.
- What is the most important thing you are concerned about during the planting and harvesting season?
- How do you usually maintain the crops and control the quality of fruits and vegetables?
- How do you keep pests and diseases away from your crops? Do you use pest control or fertilizers? (Backup question)
- Where and how do you typically sell your produce? (e.g., local markets, direct sales, contracts with wholesalers or retailers)?
- Do you regularly record the relevant information regarding farming? (such as production (physical) and financial (income/expense) information)
- When buyers would like to see the certificate (such as organic) (or other documents), how do you collect and show the certificate to them?

Section 3. Desired outcome

- Do you use any tools for planting and harvesting fruits and vegetables? Please explain the process.
- What methods and tools do you think might improve your productivity in managing and producing crops?
- What certifications or value-added procedures would you like to implement to raise the value of fruits and vegetables in the market?
- What direct marketing opportunities exist, and how can you take advantage of them?
- Do you need the tools to help record the relevant information regarding farming?
- What kind of digital platform interface would be easiest for you to use?"

Section 3. Pain point

- What is the biggest challenge you find during your crop cultivation period? Can you explain the current situation?
- How does the challenge affect your daily operation?
- How do you usually deal with the challenge?
- What pest management strategies do you employ, and how effective have they been?
- What specific weather-related challenges do you face during different stages of crop cultivation?
- How do challenges related to transportation, storage, and post-harvest handling impact the quality and marketability of fruits and vegetables?
- Do you have any problems or obstacles when recording the relevant information regarding farming?
- Do you encounter any problems or difficulties in collecting and showing the certificate (or other documents) to them?

Sustainable Impact

- How do you minimize pesticide/fertilizer use and runoff into waterways?
- How do you manage water usage and irrigation on your farm?
- Do you use any environmentally friendly practices in your farming operations (e.g., organic farming, crop rotation)

A2. Logistics company (Transporter)

Section 1. Demographic questions for other stakeholders (Logistics companies, Manufacturers, Retailers, Consumers, Thailand Greenhouse Gas Management Organization Government Agency, Organic Certification Agencies, Food and Drug Administration (FDA), Ministry of Agriculture and Cooperatives, and Technology developers)

1. Gender

- Male
- Female

2. Age

- 20–30
- 31–40
- 41–60

3. Income (Baht)

- 0–20,000
- 20,001–40,000
- 40,001–60,000
- 60,001–80,000
- 80,001–100,000
- More than 100,000

4. Education Level

- Secondary education
- Vocational Certificate/ Diploma
- Bachelor
- Master
- PhD

Section 2. Behavior questions

- How do you prioritize your tasks and responsibilities in a fast-paced logistics environment
- What types of transportation modes (e.g., truck, rail, air) do you use most? How do you choose this transportation?
- How do you develop routing routes based on client requests or other criteria, and what is the rationale behind your approach?

Section 3. Desired outcome

- What improvements do you anticipate in customer satisfaction because of refining your delivery processes?
- How can you provide real-time shipment tracking and proactive communication to customers?
- What do you expect to achieve by optimizing your routing and scheduling processes?

Section 4. Pain point

- Which is the best way to improve processes to reduce delays and improve overall delivery speed?
- How can you minimize damage to goods during transportation and handling?
- How can you improve collaboration and information sharing with other stakeholders in the supply chain (e.g., warehouses, customs)?
- What difficulties have you experienced when using digital platforms or apps for your operations?

Section 5. Sustainable Impact

- What initiatives have you undertaken to reduce greenhouse gas emissions from transportation?
- What technologies/practices have you adopted to improve supply chain visibility and traceability?
- How do you minimize waste, energy, and resource use in your warehouse/distribution operations?

A3. Manufacturer

Demographics: Apply A2 Section 1.

Section 2. Behavior

- What is your daily production capacity for organic processed foods?
- How do you ensure organic integrity during processing?
- How often do you review and update your production methods?

Section 3. Desired Outcomes

- What technological advancements would improve your organic food processing efficiency?
- What certifications or standards do you aim to achieve or maintain?
- What information do you wish to communicate most effectively to retailers and consumers?
- What kind of relationship do you seek to establish with retailers?

Section 4. Pain Points

- What are the main challenges you face in sourcing organic ingredients?
- What difficulties do you encounter in maintaining organic certification?
- What are your biggest hurdles in scaling organic production?

Section 5. Sustainable Impact

- What environmental practices have you implemented in your production process?
- How do you minimize waste and maximize resource efficiency?
- What methods do you use to reduce your carbon footprint in production and distribution?

A4. Retailer

Demographics: Apply A2 Section 1.

Section 2. Behavior questions

- How often do you interact with customers on a typical workday?
- How many times do you make purchases for your store, and what kind of products do you purchase most?
- How do you handle customer complaints or feedback?

Section 3. Desired outcome

- What methods and tools do you think might improve your productivity when purchasing processed food?
- What kind of information do you want to see in each product? Why?
- What do you expect from a food producer?

Section 4. Pain point

- Do you have problems purchasing processed food?
- What pain points hinder you from reaching the desired outcomes of proceeded food consumption?
- What is the biggest challenge you currently face as a food retailer/ distributor company related to processed food products?
- What difficulties have you experienced when using digital platforms or apps for your operations?

Section 5. Sustainable Impact

- What environmental and social criteria do you use when selecting suppliers and products?
- How do you monitor your supply chains to ensure compliance with your sustainability standards?

- What transparency and traceability requirements do you have for suppliers?
- How do you communicate environmental claims and product sourcing to consumers?

A5. Consumer

Demographics: Apply A2 Section 1.

Section 2. Behavior questions

- Where do you buy processed food, and how many do you purchase each time?
- Why do you consider buying processed food?
- Do you think processed food is bad for your health?
- What factors do you consider before buying processed food?
- Are you interested in looking for nutrition content claims or health claims on food before deciding on food choices?

Section 3. Desired outcome

- What specific features of processed food do you want?
- What do you expect from eating processed food?
- Do you expect processed food to be good for your health?

Section 4. Pain point

- Do you have problems related to proceeded food consumption?
- Is it difficult to find processed food that satisfies your taste preferences?
- Do you think it is challenging to buy processed food?
- Do you have any health problems from eating processed food?

Section 5. Sustainable Impact

- How important are environmental and social factors in your purchasing decisions?
- What types of sustainability labels most influence your brand/ product choices?
- How much are you willing to pay more for environmentally/ethically produced goods?

A6. Thailand Greenhouse Gas Management Organization Government Agency

Demographics: Apply A2 Section 1.

Section 2. Behavior questions

- How do you prioritize your tasks and responsibilities within the Thailand Greenhouse Gas Management Organization Government Agency?
- What barriers, if any, prevent you from engaging in more environmentally friendly behaviors?
- What motivates you to perform well in your role within the Thailand Greenhouse Gas Management Organization Government Agency?
- How do they measure the carbon footprint? (calculation, collect the data, what kind of data, tool)
- What factors can influence the measurement of carbon emission?

Section 3. Desired outcome

- Are there any areas in the Thailand Greenhouse Gas Management Organization Government Agency that you feel could be improved? Why?
- What do you expect to improve your operation in the Thailand Greenhouse Gas Management Organization Government Agency?
- How do you envision your role contributing to the overall reduction of greenhouse gas emissions in the organization?

Section 4. Pain point

- What are the main challenges or obstacles you face in implementing effective greenhouse gas management practices?
- How do these challenges impact your day-to-day work and overall effectiveness in managing greenhouse gas emissions?
- Are there any specific areas or processes within the organization that you believe could be improved to better support greenhouse gas management efforts? If so, please describe.
- What are your key concerns regarding data interoperability and standard formats when developing or using digital platforms

Section 5. Sustainable Impact

- What programs or policies encourage companies to measure and reduce emissions?
- How do you validate corporate emissions reporting and offset claims?
- What guidelines exist for product/supply chain emissions calculations and disclosure?
- How do you support industries in adopting cleaner technologies and reducing their carbon footprint?

A7. FDA

Demographics: Apply A2 Section 1.

Section 2. Behavior Questions

- How do you balance the need for thorough safety reviews with industry pressure for faster approvals?
- What methods do you use to track and verify food safety compliance data?
- Which factors most significantly influence your decision-making process during safety assessments?

Section 3. Desired Outcomes

- What improvements would you suggest for the current food safety inspection system?
- How could the FDA's approach to emerging food technologies be enhanced?
- What additional resources or tools would help you perform your duties more effectively?

Section 4. Pain Points

- What are the main challenges in enforcing food safety regulations across diverse food industries?
- How do staffing and resource limitations impact your ability to conduct thorough inspections?
- What difficulties do you face in keeping up with rapid innovations in food technology?

Section 5. Sustainable Impact

- How do you evaluate the environmental impact of food production methods during inspections?
- What initiatives exist to promote sustainable packaging in the food industry?
- How do you balance food safety requirements with sustainability goals?

A8. Organic Certification Agency Questionnaire

Demographics: Apply A2 Section 1.

Section 2. Behavior Questions

- How do you verify compliance with organic standards throughout the supply chain?
- What is your process for conducting organic certification audits?
- How frequently do you review and update certification criteria?

Section 3. Desired Outcomes

- What improvements would make the organic certification process more effective?
- How could technology be better utilized in organic verification?
- What additional training or resources would enhance certification accuracy?
- How do you envision organic standards evolving to meet future challenges?

Section 4. Pain Points

- What are the main obstacles to maintaining consistent certification standards?
- How do you address the challenges of international organic trade requirements?
- What difficulties arise in verifying compliance throughout the entire supply chain?

Section 5. Sustainable Impact

- How do organic certification requirements contribute to environmental sustainability?
- What methods do you use to assess the environmental impact of certified operations?
- How do you help producers transition to organic practices?

A9. Technology Developer
Demographics: Apply A2 Section 1.
Section 2. Behavior questions

- How do you usually develop new technology? What steps do you take?
- Do you have experience in developing traceability technology?

Section 3. Desired outcome

- What do you think about the traceability platform looks like?
- What do you expect from traceability technology?
- Is there any equipment or tool that could facilitate the work successfully?

Section 3. Pain point

- What are the challenges you face when you build the technology for food traceability?
- How do you usually debug or find the error in the system?
- What data security measures are critical for you to trust a digital traceability system?

Sustainable Impact

- How do you ensure data accuracy and security and prevent fraud in traceability systems?
- What analytics or reporting capabilities help identify environmental/social hotspots?

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