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Digitalizing traditional agri-food supply chains in developing economies: A pathway to regulated sustainable governance

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ABSTRACT

This study presents a comprehensive framework for digitalizing traditional agri-food supply chains (TASCs) in developing economies, paving the way towards digital transformation. Digitizing is the initial step of digital transformation, which is the conversion of analog information into digital form. Digitalization is the use of digital technologies to improve existing processes, and digital transformation is the comprehensive integration of digital technologies to fundamentally reshape operations and business models. TASCs in developing economies rely on manual information, leading to inefficiencies and resource wastage. Employing an abductive reasoning approach, the study investigates a case study in a developing economy. A social network analysis was conducted along with process mapping for the identified case study to evaluate stakeholder interactions, identifying key metrics like degree centrality, betweenness centrality, and closeness centrality. The study identified farming input suppliers, agriculture field officers and distribution center managers as critical influencing stakeholders in this social network. The framework introduced in the study emphasizes regulated digitalization, where governing bodies oversee seed supply and production planning to ensure alignment with market demand. The proposed framework offers benefits for all supply chain stakeholders while improving transparency, optimizing resources, leading to improved production planning, minimized post-harvest wastage, reducing price volatility and increasing food security. The framework offers strategic insights for both policymakers and researchers aiming to modernize TASCs by triangulation of data with stakeholder benefits. Overall, this study provides a structured roadmap for digitalizing the TASCs in developing economies, laying the foundation towards digital transformation and agricultural sustainability.

1. Introduction

In an era characterized by rapid technological progress, the digital transformation of agri-food industries has emerged as an influential force for a sustainable future [1]. This transformation, driven by the integration of digital technologies into core operations, has led to increased efficiency, competitiveness, and sustainability across various agri-food sectors worldwide [2]. Digitization refers to the conversion of analog information into digital format, digitalization relates to the enhancement of business processes by digitization, and digital transformation involves the changes of business models facilitated by digitalization [3]. The agricultural industry, a critical cornerstone of livelihoods and food security in developing economies, is no exception to this change [4]. It is significantly important to embark on an exploration of the significant role that digitization and digitalization can play in reshaping traditional agri-food supply chains, including Traditional Vegetable Supply Chains (TVSCs) within the context of developing economies [1–4]. The worldwide shift toward digital transformation and innovative business models is changing the way many industries work [5]. Its impact is especially significant in agriculture, where it can make a big difference for millions of small-scale farmers and the economies [1]. Hence, as global operations become more connected and rely more on data, there is a growing need for developing economies to use digital tools to improve their agricultural supply chains [6,7].

The absence of digital tools and analytical models further increases the complexity of managing these supply chains, leading to inefficiencies in production planning, logistics processes, and demand

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planning [8]. Due to this limited access to real-time data and information, smallholder farmers in developing economies often struggle in the decision-making process to gain a proper price, contributing to revenue losses and market imbalances [9]. The inefficiencies in logistics are adding another layer of disruption to the agri-food supply chain. These inefficiencies contribute to post-harvest losses due to the perishable nature of agricultural products and increase the lead time for delivering goods to end consumers [10]. Given these challenges, there is an urgent requirement for policy interventions to promote data-driven decision--making and enhance logistics processes [2]. Through the collaboration of governments and industry stakeholders, policies can be developed to promote and support the digital transformation process starting from digitization. This process will help to reduce the inherent risks and failures in the current agri-food supply chains due to the lack of reliable supply chain data [4]. These policy interventions can be designed to enhance sustainability and resilience in agri-food supply chains [9]. They will help withstand external shocks, reduce uncertainty and risk, and protect key stakeholders, particularly farmers and consumers, through data-driven policy and decision making. However, due to the lack of collaborative platforms and national policies, accurate data is not available in the policy developing institutes in developing economies [7]. Hence, the main objective of this study is to develop a comprehensive framework that enables the path for digitalizing agricultural supply chains in developing economies.

The rest of the paper follows this structure. Section two covers the literature background with the research gap and section three explains the research methodology, case study and data collection process along with the methods employed in data collection. The analysis is also covered in the third section, including the process mapping and social network analysis. Section four contains the results and discussion along with the digitalization architecture as a novel initiative for the digitalization of the TVSCs in developing economies. As the final remarks, section five summarizes the study by the conclusion with insights for industry practitioners and decision makers.

2. Literature background

This section explores different supply chain strategies that have been examined by different scholars with the objective of improving the social, economic and environmental sustainability in developing economies. These supply chain strategies highlight the importance of employing different strategies to enhance the sustainable performance of agri-food supply chains. This section also points out gaps in the existing research, mainly when it comes to how important it is to use integrated approaches that combine digitalization with regulatory mechanisms for sustainable supply chain management of agri-food supply chains.

2.1. Supply chain strategies employed in agri-food supply chains

There are several research that have been conducted to enhance the agricultural supply chains while improving their efficiency and sustainability. We can find similarities in each researcher's strategies despite their different study focuses. As shown in Table 1, some of the most important strategies that have been used in the past are Digital Transformation and Technology Integration (DTTI), Sustainable Practices and Regulatory Frameworks (SPRF), Supply Chain Management and Infrastructure Development (SCMID), Capacity Building and Community-Based Approaches (CBCA), and Financial Innovations and Risk Management (FIRM). Especially, these studies have shown the importance of employing these strategies in the agriculture sector in developing economies.

Among these strategies identified as per Table 1, DTTI and SPRF emerge as foundational enablers toward enhancing sustainability in agrifood supply chains in developing economies. DTTI is capable of bringing transparency and connectivity, enabling data-driven decision-making and improved resource allocation. Meanwhile, SPRF ensures long-term sustainability by addressing regulatory compliance. The combination of these two strategies has the potential to create a pathway for agri-food supply chains to evolve toward resilience, equity, and sustainability while allowing other strategies such as SCMID, CBCA, and FIRM to be implemented more effectively.

2.2. Digital transformation and technology integration

Recent literature underscores the transformative potential of DTTI, emphasizing its pivotal role in enhancing efficiency, sustainability, and resilience across diverse agricultural contexts [1]. The process of digital

Table 1
Empirical studies conducted to enhance agri-food supply chains.

Researchers	Focus	Strategy Category				
		DTTI	SPRF	SCMID	CBCA	FIRM
Lee and Choe [11]	Comparing the environmental performance of organic and conventional soybean farming.		✓			
Akenroye et al. [12]	Identifying barriers to sustainable practices in coffee farming stages.		✓			
Ali et al. [13]	Exploring farmers' perceptions and strategies to cope with climate change.				✓	
Khanal et al. [14]	Assessing smallholder farmers' adaptations to climate change and productivity.		✓			
Nguyen and Drakou [15]	Investigating factors influencing Vietnamese farmers' intention to adopt sustainable practices.				✓	
Ojo and Baiyegunhi [16]	Assessing climate change perception's impact on rice farmers' net income.				✓	
Yi et al. [6]	Exploring financing options for capital-constrained smallholder farmers' supply chains.					✓
Azizsafaei et al. [17]	Assessing risks in dairy supply chains using system dynamics modelling.			✓		
Branca et al. [18]	Assessing factors limiting technology adoption in smallholder agriculture in Africa		✓			
Giger et al. [19]	Examining smallholder livelihoods about commercial farms in Kenya.				✓	
Scudder et al. [20]	Evaluating financial viability of cocoa pest management systems.					✓
Tuni et al. [21]	Identifying barriers hindering commercialization for smallholder farmers in Malawi.			✓		
Zhang et al. [22]	Examining the Internet's impact on reducing farmers' poverty vulnerability in China.	✓				
Abdulai et al. [1]	Examining how digitalization transforms smallholder farming practices in Ghana.	✓				
Camacho-Villa et al. [23]	Examining social ties' impact on resilience in maize farming systems				✓	
Clavijo-Buritica et al. [24]	Designing resilient agri-food supply chains for Colombian coffee production.			✓		
de Vos et al. [25]	Investigating harvest practices to improve yields in Indonesian palm oil.		✓			
Hammond et al. [26]	Analyzing poverty dynamics and factors affecting East African smallholders				✓	
Li et al. [27]	Examining labour migration's effect on fertilizer use mediated by services.				✓	
Moreira-Dantas et al. [28]	Assessing credit acquisition factors for family farming in Legal Amazon					✓
Ume [29]	Market access is crucial for organic farming and food security benefits.			✓		
Urfels et al. [30]	Small farm sizes hinder poverty reduction despite irrigation-led intensification			✓		
Fernando et al. [31]	Mobile phone literacy's impact on sustainable smallholder agri-food supply chains.	✓				
Jelsma et al. [32]	The resilience of farmer organizations and replanting strategies in Indonesia.		✓			
Pinca et al. [33]	Evaluating benefits of wild and domesticated olive cultivation in Nepal.		✓			

transformation unfolds in three key stages. These stages are digitization, digitalization, and finally digital transformation [31]. Digitization marks the initial step in transitioning a paper-based supply chain into the digital era. This phase involves converting physical records, such as delivery notes, purchase orders, and invoices, into digital formats [5]. By doing so, data can be swiftly shared across various platforms while ensuring accuracy in record-keeping. Digitalization comes next and revolves around leveraging digital technologies to enhance existing processes [2]. In the context of agricultural supply chains, this entails the application of technologies like Internet of Things (IoT) devices, drones for precision agriculture, and data-driven analytics [1–34]. These tools enable real-time monitoring of product flow throughout the supply chain, allowing for tracking of transport processes, product quality, and inventory levels [21]. Additionally, digitalization promotes improved coordination and communication among different supply chain participants, including farmers, distributors, and retailers [1–34]. Digital transformation represents the comprehensive overhaul of processes, made possible through the integration of digital technologies. This might involve the development of entirely new business models that harness digital technologies to create novel value propositions for customers. These innovations signify a profound shift in how the supply chain operates and delivers value [31].

2.3. Sustainable practices and regulatory frameworks

SPRF are vital for promoting sustainable farming practices and ensuring compliance with standards that protect both the environment, the farmer community and consumers [12]. The existence of SPRF ensures the long-term resilience of agri-food supply chains. Additionally, it enables data-driven policy decisions, ensuring they are evidence-based. It provides the necessary structure to drive sustainability and ensure compliance with policies. Well-designed SPRF have the capability to mitigate risks while improving the resilience, which ultimately protects both consumers and farmers. Hence, they are essential to agri-food supply chains since they provide structured guidelines that facilitate the adoption of sustainable interventions while maintaining economic viability [17].

2.4. Research gap and research questions

Given this context, digitization is the initial stage that guides this digital transformation process [3–31]. Although the advantages of digitization and digitalization are quite persuasive, the path toward achieving digital transformation in developing economies is difficult due to several challenges and barriers [12–31]. One main concern is inaccurate agrarian data, including production and market data, due to the lack of digitization. Most of the data are inaccurate since these are based on biased and misaligned forecasting, which does not reflect the ground reality. Hence, using these data can lead to decisions that impact agricultural policy development and market stability. Consequently, any strategy formulated for digitizing and digitalizing agricultural supply chains must be custom-tailored to address these distinct challenges and guarantee fair access to the benefits it offers [35]. Furthermore, empirical studies highlight how digitalization enables real-time monitoring, traceability, and transparency, facilitating improved decision-making and supply chain coordination [2–36]. However, developing countries have been slow to adopt digital technologies, leading to persisting inefficiencies [14].

As we noticed, there is a lack of research that highlights the importance of a holistic, systematic approach to developing a regulatory framework to optimize agricultural supply chains through digitalization while ensuring sustainable aspects [1]. Hence, through this study, we are exploring how we can employ digitization collectively with digitalization, sustainable practices and regulatory frameworks. For this reason, this study addresses this research gap by exploring solutions to the below research questions.

R.Q.1. What are the current bottlenecks and influencing factors for streamlining the information silos in the traditional vegetable supply chains in developing economies?

R.Q.2. How to develop a centralized and digitalized system that aggregates and promotes interaction between the traditional vegetable supply chains to reduce waste?

3. Methodology

A case study provides better insights to identify patterns and trends of a specific concern. This approach helps to understand the complexities, unique characteristics and dynamic nature of a case which has been under-investigated [37]. Therefore, this study adopts a case study-based abductive approach, as abductive reasoning allows iterative movement between empirical observations and theoretical constructs [38]. Since this study covers a global scenario, the abductive approach helps to theory improvement through real-world complexities [38]. A case study-based abductive approach is usually investigating employing tools such as interviews, observations, documents, and multiple sources of data [38,39]. Therefore, this combination has been employed in this study since it provides a deeper understanding of the complexities inherent in the real-world context. Adding to that, this combination allows for the generation of creative theoretical insights as well as practical insights. Fig. 1 summarizes the methodology we employed in this study. As the first step, a case study analysis was used to understand the current state of agri-food supply chains in developing economies and gather data to develop the As-Is state process map. In the second step, collected data were examined using social network analysis. It helps to visualize and measure relationships among stakeholders, identifying influential actors and bottlenecks in information and resource flow. The final step integrates findings from the case study analysis and social network analysis to develop a digitalized regulatory architecture to improve supply chain coordination, transparency and efficiency among stakeholders.

3.1. Step 1 - case study analysis

3.1.1. Selection of case study

The selection of the Sri Lankan vegetable supply chain as our case study area is both purposeful and relevant to the research undertaken. Sri Lanka's agricultural landscape, characterized by its predominantly smallholder farmers and the vital role of vegetables in the country's food security, presents a compelling context for the study of digitalization in agricultural supply chains within developing economies. The challenges and opportunities unique to this setting, including unavailability of infrastructure, fragmented and lengthy supply chain structures, and an expanding demand for digitalization, make it a suitable case study for investigation. By examining how digital technologies can enhance efficiency, transparency, and sustainability, insights can be applied to other developing economies as well [37]. Focusing on this specific case study, we aim to develop a robust framework tailored to the Sri Lankan context. This approach will also contribute valuable insights and best practices that can inform digitalization efforts in similar agricultural supply chains across other developing economies.

As the case study we have selected Sri Lanka, as presented in Fig. 2, which is a developing nation in the Asian region. With a population of approximately 21 million people across more than 65 000 km^2, the nation exhibits a diverse culture. Like many developing economies, Sri Lanka faces challenges in sectors such as education, healthcare, and infrastructure development. The economy, primarily driven by agriculture, services, and industry, aligns with the diversified economic structures often found in developing nations. In Sri Lanka, agriculture plays a pivotal role in the nation's economy, contributing a significant 7.1 % to the gross domestic product in 2020 and providing employment to approximately 27.12 % of the labour force, both directly and indirectly [40]. This sector's impact extends beyond its boundaries,

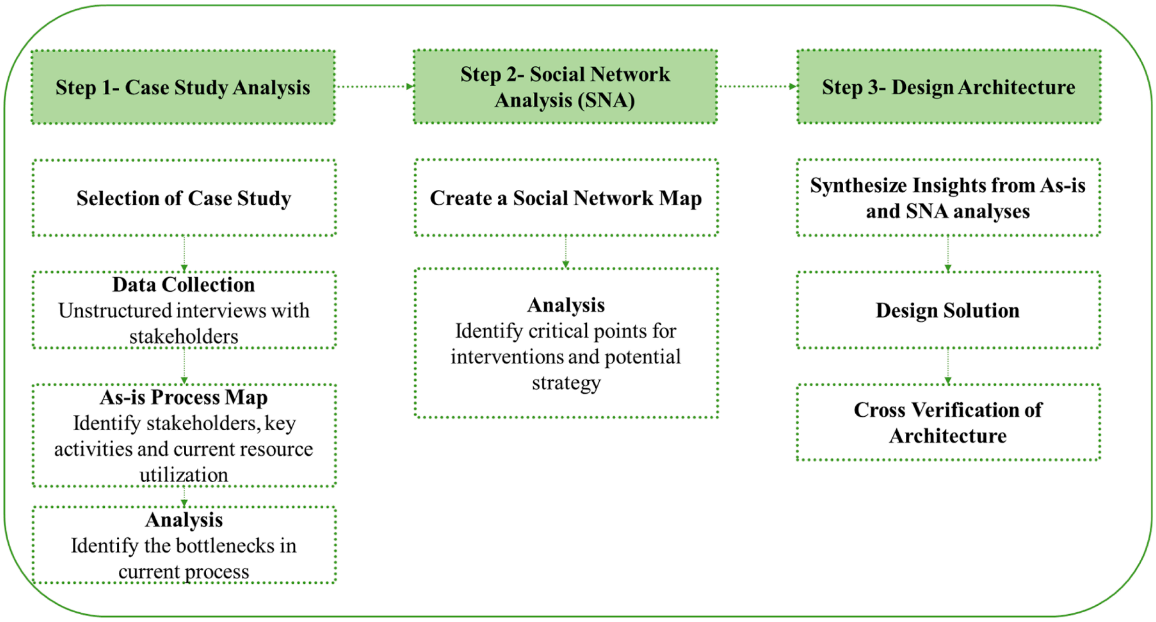

Fig. 1. Research design.

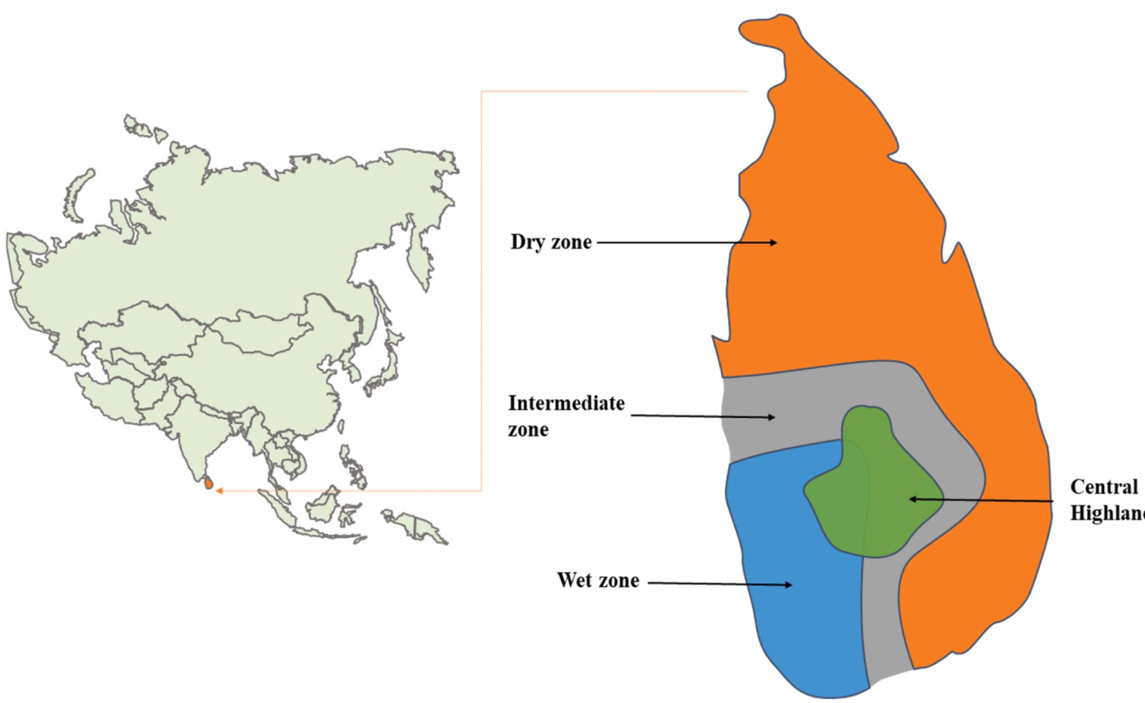

Fig. 2. Map of case study area.

influencing industries such as consumer packaged goods, retail, and tourism, underscoring its significance.

The vegetable supply chains in Sri Lanka are categorized into two distinct systems: the Traditional (i.e., intermediary-driven) vegetable supply chains and Modern (i.e., supermarket-driven) vegetable supply chains. The TVSCs handle a significant portion of vegetable and fruit production, satisfying 67 % of total consumer demand in Sri Lanka [41]. This supply chain predominates due to the prevalence of small-scale farmers with land holdings typically not exceeding two hectares, with 80 % contribution of the total annual production. Most of these farmers are located in remote areas and serve as the primary producers within this supply chain. A key limitation of the TVSC is the farmers' lack of bargaining power and technical knowledge. This deficiency, combined with limited access to information and low transparency, results in increased inefficiencies throughout the supply chain. The fragmented nature of this supply chain further impedes the flow of supply and demand information among stakeholders, making it challenging to respond to dynamic demand patterns. The TVSC in the case study country, which represents the most prevalent model, encompasses several key components as per Fig. 3.

However, the agricultural landscape of the country has been gradually diminishing over recent decades due to limited infrastructure, including unavailability of cold supply chains and deficiencies in the supply chain network connecting farmers and consumers. This

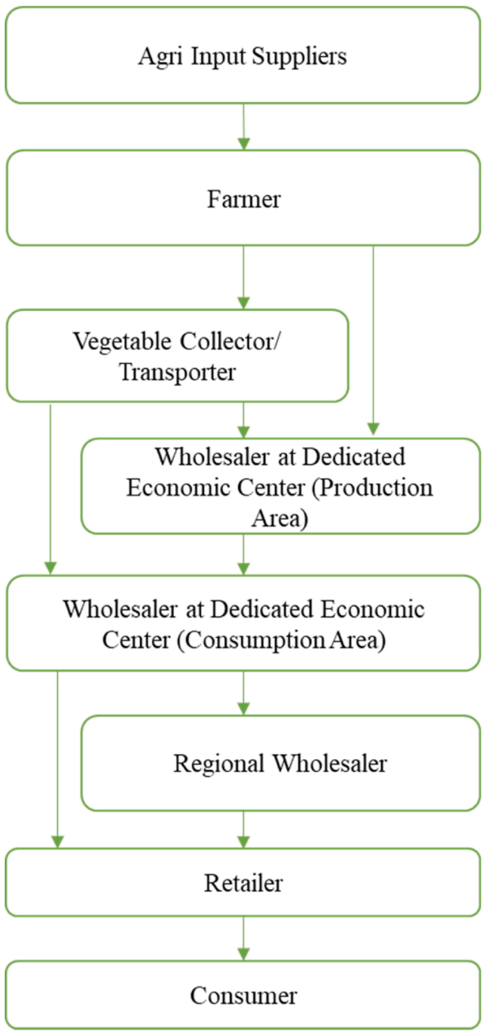

Fig. 3. Generic traditional vegetable supply chain.

suboptimal supply chain has led to disparities, leaving both farmers and consumers at a disadvantage. Additionally, the issue of post-harvest waste appears large, with estimates suggesting that between 30 % to 40 % of the total produce has been wasted in recent years, resulting in increased costs for consumers [42]. The management of this supply chain has been further complicated by a lack of transparency and the complexity of measurements due to heterogeneity within the industry. To address these challenges, the agricultural sector must undergo a digital transformation enabled by enhanced digital connectivity [43].

3.1.2. Data collection

In our pursuit of digitalizing the agricultural supply chain in the case study country, the initial step involved a comprehensive background exploration. This process was instrumental in understanding the specific requirements and challenges inherent to the vegetable supply chain. We adopted a multifaceted approach to gather essential data, encompassing both quantitative and qualitative dimensions. Direct observation and unstructured interviews with stakeholders were employed as two key methods for data collection. Direct observation provides an unbiased understanding of the current state without being biased toward stakeholder opinions. Unstructured interviews allow for in-depth exploration of stakeholder perspectives and reveal hidden challenges. The combination of these two approaches provides a holistic and balanced understanding of the current state.We conducted data collection through direct observation at four significant dedicated economic centers (DECs) in the case study country (i.e., Keppetipola DEC, Dambulla DEC, Thambuththegama DEC, and New Manning Market, Peliyagoda). These DECs play a vital role in the large-scale collection and distribution of vegetables from various regions in the case study country. Specifically, Keppetipola DEC, Dambulla DEC, and Thambuththegama DEC are primarily responsible for gathering vegetables directly from farmers and collectors. Then, they distribute these vegetables to densely populated areas around the country, often through intermediaries like wholesalers. The New Manning Market, Peliyagoda, serves as another significant hub for vegetable collection and distribution, specializing in addressing the vegetable production shortfall within the Western Province, which experiences high population density but lower vegetable production compared to other DECs in their respective areas.

Through direct observation, we engaged in the inner workings with the supply chain actors, thoroughly documenting every step of the vegetable collection, sorting, packaging, and distribution processes within the DECs. This hands-on approach offered a deep understanding of the operational intricacies and bottlenecks, forming the foundational knowledge for our framework development. We conducted unstructured interviews with stakeholders to collect their opinions on the improvements that can be made to uplift the TVSCs. Through these interviews, we gained valuable insights into the intricacies of the vegetable flow within the supply chain. In these interviews, we collected how the respondents were connected with other stakeholders and the relationships among different stakeholders to provide trust and value. These interactions not only informed our framework but also served as a platform for stakeholders to provide their perspectives, challenges, and aspirations regarding digital transformation within the agricultural sector. A summary of stakeholders involved in the data collection is depicted in Table 2.

3.1.3. As-Is process map

Understanding the current state, or the "As-Is" state model, is pivotal in the search for ways to enhance agricultural supply chains. This phase provides a foundational understanding of the existing systems and processes that drive the TVSC in the case study country. To transform and digitalize this vital sector successfully, recognizing the complex network of stakeholders, activities, and data flows within the current supply chain is essential [44]. Swim Lane Modelling prove highly advantageous, especially given the application's fundamental data accessibility and their ability to provide a robust visualization of information encompassing actors, activities, processes, and data within the study area [45]. Moreover, this technique facilitates effective communication of process information and the interactions among stakeholders, thereby establishing the initial path for software development. Therefore, we utilized Swim Lane Modelling which is also known as Cross-functional Flow Process Mapping method, to model the current state of the vegetable supply chain in our case study since it illustrates how a process flows across multiple functional areas, visualizing stakeholder interactions.

3.2. Step 2 - social network analysis

Social Network Analysis (SNA) is employed as the method to unravel the complexities of the agricultural supply chain stakeholder network. SNA involves a systematic analysis of social structures through the use of network and graph theories, allowing for the visualization and interpretation of complex relationships between various stakeholders [46].

Table 2
Summary of data collection.

Supply Chain Actor	Number of Interviews
Farmers	42
Agricultural field officers	6
Wholesalers at distribution centers (i.e., DECs)	44
Administration managers of distribution centers (i.e., DECs)	4

By focusing on the interactions and transactions among the stakeholders, SNA can be used to visualize the network with nodes representing the stakeholders, while edges depict the relationships or interactions between them. SNA enables identifying key players, influential nodes, and potential bottlenecks in the supply chain network by considering network metrics such as degree centrality, betweenness centrality, and closeness centrality [47]. This visualized network and calculated metrics can provide insights into the efficiency, transparency, and potential collaboration within the supply chain. This helps in identifying areas for improvement and developing targeted interventions in the change management of the system. The analysis was conducted using R version 4.3.2, using the package igraph and the Network diagram was developed using Gephi 0.1, which is a visualization software.

3.3. Step 3 - design architecture

We develop an architecture that can be integrated into the TVSC as an effective solution through the insights received from the As-Is process map and the social network analysis. This involves integrating findings from the existing system (with network dynamics identified through SNA to craft a tailored architecture that addresses identified inefficiencies and leverage points of the TVSC). Based on these synthesized insights, we design a comprehensive architecture that aligns with the goals of enhancing efficiency, transparency, and sustainability within the TVSC in developing economies. We used Cross-functional flow process mapping, and the used notations are as per Fig. 4.

3.4. Process mapping

In this section, we examine the details of the developed As-Is model, identifying the core components and dynamics that govern the TVSC in the case study country. The developed As-Is model visualized in Fig. 5 serves as a comprehensive representation of the TVSC in the case study country.

It begins with the Farming Input Suppliers (FIS) in the 2nd row of

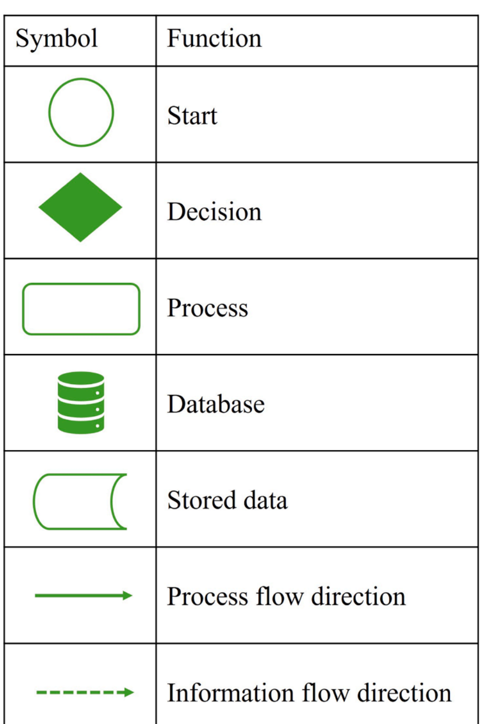

Fig. 4. Cross-functional flow process mapping diagram notations.

Fig. 5, involving the stakeholders responsible for providing resources such as seeds, pesticides, and fertilizers to the farmers. FIS are required to obtain the necessary approvals from the Government Agriculture Policy Institute (GAPI) and Agriculture Input Regulatory Authority (AIRA) in the 1st row of Fig. 5 before importing agri-inputs. They undergo an evaluation process to assess the suitability of the imported materials for the local context. If the specifications of the imports intended by the farming input suppliers align with the approved standards set by governmental regulatory bodies, the requests receive approval. Subsequently, farming input suppliers import the required inputs and distribute them across the case study country through Authorized Sellers (AS) in the 2nd row of Fig. 5. Farmers (F) and Farmer Societies (FS) in the 4th row, as per Fig. 5, purchase the farming inputs through them and start the cultivation process.

In the current TVSC of the case study country, the process of information collection remains entirely manual. Agricultural Field Officers (AFO) in the 3rd row, as per Fig. 5, make periodic visits to farmers' lands to gather essential information and offer guidance for achieving successful harvests. Their data collection efforts typically encompass details about the farmers, their land, crops, and, if applicable, information regarding farmer associations. AFO shoulders the responsibility of collecting and conveying this information to the government regulatory bodies and authorities. Additionally, when farmers in their assigned areas request advisory services, AFO is required to visit the farmers, assess the issue, and provide guidance on corrective measures. The farmers, constituting the backbone of the supply chain, are the primary producers who cultivate the vegetables that eventually reach consumers' tables. In the common scenario, farmers are tasked with sorting, cleaning, and packaging using materials such as gunny bags or wooden crates. To sum it up, farmers play a significant role in performing most of the value-adding tasks within this value chain under the guidance of AFO.

Moving forward within the model, we encounter the pivotal role played by vegetable collectors or transporters in the 5th row as per Fig. 5. These intermediaries act as a bridge between the agricultural hinterlands and the strategically located DECs in the production areas, gathering freshly harvested produce from the farmers. In some instances, these collectors or transporters themselves may also be farmers from the same region, adding a layer of complexity to the supply chain dynamics. Within the DECs, Distribution Center Wholesalers (DCW) in the 6th and 8th rows, as per Fig. 5, have the responsibility of product distribution. They ensure that the vegetables reach consumers efficiently while maintaining a profit margin. This profit margin or commission margin changes from each regional DEC due to different reasons. This margin is 5 % or 10 % of the revenue received after selling the harvest of the farmer to the next-tier wholesalers or retailers. The Distribution Center Manager (DCM) in the 7th row, as per Fig. 5, is responsible for recording the average pricing details for the sold products at the distribution center. This is the only record which they keep related to market information.

Throughout the buying and selling processes, bargaining and negotiation are common practices similar to an auction. Notably, in the DEC operations, there is a turnaround time of a maximum of 24 h for the vegetables brought into the facility. This means that harvested vegetables are distributed to retailers in the consumption areas within a day most of the time without considering the excess of seasonal vegetable production. The payment for the harvest of the farmers can be facilitated in two ways, depending on the convenience and preference of the farmers as per the 4th and 6th rows of Fig. 5. If a farmer has easy access to banks and is comfortable with online transfers, the wholesaler in the production area directly transfers their share via bank systems. Alternatively, if a farmer does not have easy access to banks, wholesalers in the DECs in the production regions arrange for the payment to be sent through the transporters who brought the harvest to the wholesalers at the DECs.

Subsequently, retailers in the 9th row, as per Fig. 5, come into play,

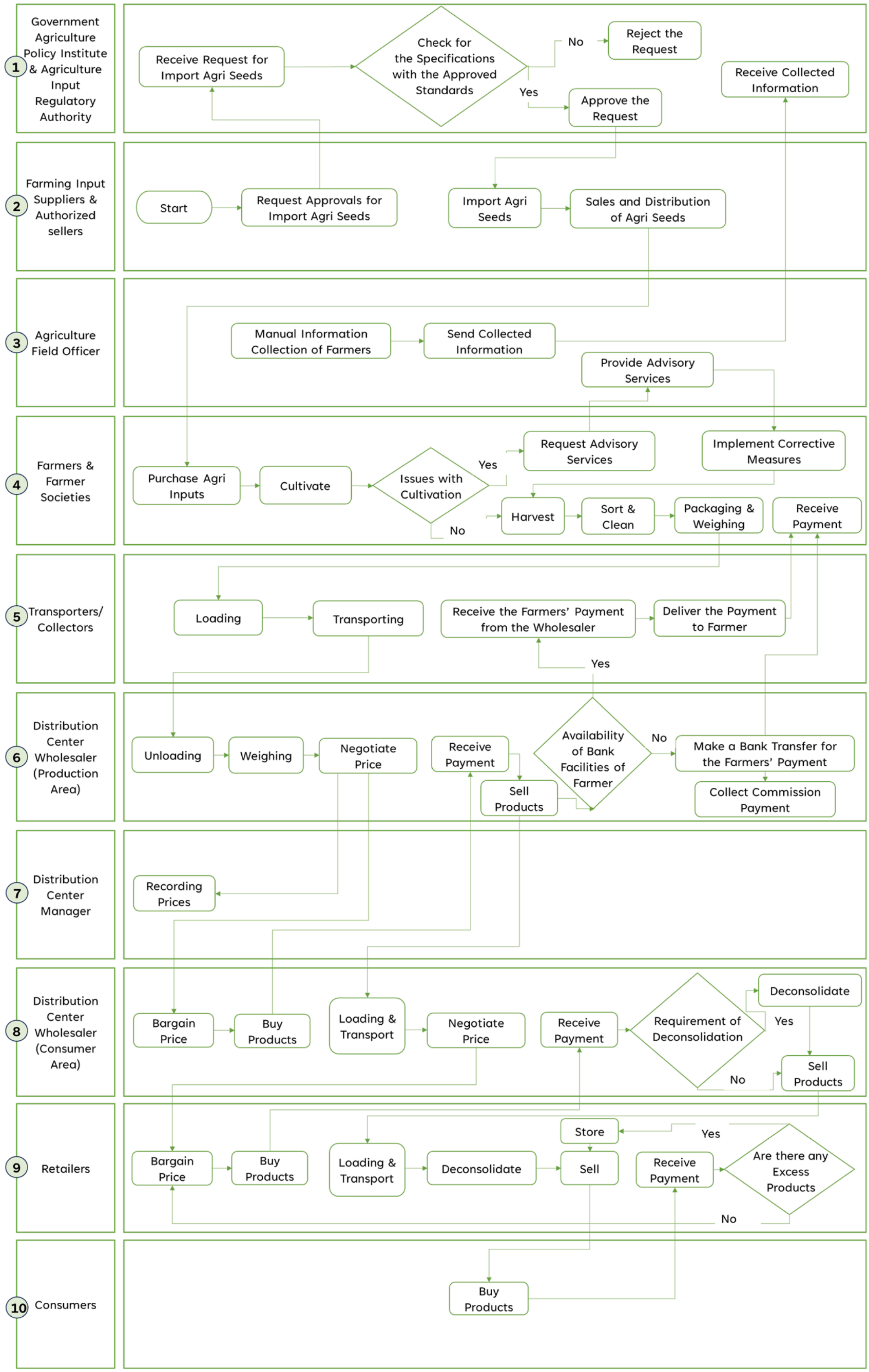

Fig. 5. As-Is state process map.

procuring the products from either regional wholesalers or wholesalers based in DECs in the consumption area. Additionally, within the retailers' segment of the supply chain, there is a process of deconsolidating the products, followed by selling them to consumers after purchasing from wholesalers. However, the retail operations store the remaining products and resell them in response to changing consumer demand. Unfortunately, most retailers adopt suboptimal storage practices, which may lead to issues at this stage. When all the products are sold to consumers, retailers repurchase the required quantity of products from wholesalers, and the entire process restarts from the beginning of the supply chain. Finally, consumers in the last row, as per Fig. 5, access their daily vegetable requirements through these retailers.

In conclusion, lengthy supply chains involve repetitive non-value-adding activities such as loading, unloading, weighing, delivering, and transporting with each intermediary action. These activities extend the lead time in the distribution process, reduce the freshness of vegetables, and contribute to post-harvest losses. Furthermore, they lead to increased price margins for fresh vegetables, resulting in higher retail prices for consumers and lower revenues for farmers. Notably, the actors in this supply chain do not take responsibility for the product's quality, as observed by the processes that add value to the product. Unless the farmer, rather than any other intermediary, is involved in value-addition processes like cleaning or sorting, the product's quality remains unassigned. By passing products between stakeholders, each actor up to the downstream wholesaler seeks to increase revenue. This results in low-quality vegetables circulating in traditional retail markets and increased post-harvest losses. Meanwhile, consumers mainly worry about product quality and price. Furthermore, there is a lack of feedback from consumers to farmers regarding quality and quantity requirements, leading farmers to rely solely on wholesaler information, potentially resulting in overproduction or underproduction and inequitable profit distribution. Adding to that, in the harvesting process, farmers tend to prioritize harvesting mature products for higher weight, resulting in higher profit, rather than focusing on product quality.

3.5. Application of social network analysis

We analyzed the relationship network between the stakeholders in the supply chain through the information given by the interviewed stakeholders. There are mainly three components in SNA that we are focusing on for this study. They are network mapping, relationship analysis, influence and centrality analysis. Our objective was to develop the network diagram while acquiring network metrics, including Degree Centrality, Betweenness Centrality and Closeness Centrality for each stakeholder. The analysis was conducted using the collected data from the conducted unstructured interviews, mainly considering the role of the stakeholder in the network, the nature of the relationship and the connectivity frequency between the stakeholders. Table 3 provides an overview of the average frequency between nodes, derived from the mode values of the responses gathered from the sample data. The stakeholders' relationships and their interaction frequencies, such as daily, weekly, or monthly. It reflects how different entities, from farmers to government agencies, are interconnected in the agricultural value chain and contribute to network dynamics. The results of the relationship analysis, influence and centrality analysis are as per Table 4.

As per Fig. 6, the network diagram visualizes the stakeholders by the nodes and their connection within the network by the edges. The proportion of the node indicates the degree centrality, which means that they are more connected within the network, thus they have more influence within the network. FIS and AFO have the largest node sizes (0.5), showing they are central hubs with many direct connections. GAPI, farmers, and DCM also have significant degree centrality (0.375), indicating their key roles in policy direction, farming activities, and distribution management. The colour of the node visualizes the closeness centrality, meaning that these nodes can quickly interact with all other nodes in the network. DCM has the highest closeness centrality (0.4711), reflecting its pivotal position in maintaining communication and interaction within the network. Farmers and DCW also have high closeness centrality (i.e., 0.347 and 0.300 respectively), highlighting their roles in ensuring an efficient flow of products and information. Betweenness centrality is visualized by their strategic position in the network, allowing them to influence multiple other nodes directly. The stakeholders with high betweenness centrality values can act as bridges between different parts of the network. Therefore, nodes like FIS, AFO and farmers are critical for controlling the flow of information and resources due to their high betweenness centrality values (0.125).

As per the results of the SNA, we must focus on connections between key stakeholders such as FIS, AFO, farmers, and DCM, as these entities are highly connected and influential within the TVSC network. Hence, if we need to bring concepts such as digital transformation, technology integration, sustainable practices, and regulatory frameworks to the supply chain, we have to focus on these stakeholders. Importantly, if we want to regulate the supply chain as per this analysis, it shows we have to regulate AIS and AFO due to their connectivity and influence in the supply chain. In order to optimize the resources in this supply chain,

Table 3
Social network relationships details.

Source	Target	Average Frequency	Nature of Relationship
GAPI	AIRA	Few times per month	Directing and controlling policy level planning and regulations
GAPI	DCM	Few times per month	Directing and controlling distribution center operations
GAPI	AFO	Few times per month	Directing, guiding, and controlling field officers to guide farmers
AIRA	FIS	Few times per month	Controlling imports and ensuring compliance with government regulations
FIS	AS	Daily	Providing farming inputs to authorized sellers
FIS	AFO	Weekly	Introducing farming inputs to increase awareness among farmers
FIS	DCM	Weekly	Introducing farming inputs to increase awareness among farmers
AS	F	Few times per season	Selling farming inputs to farmers
AFO	F	Weekly	Directing and guiding farmers through community meetings
AFO	FS	Weekly	Directing and guiding through farmer society meetings
F	DCW	Daily	Selling harvested products, receiving revenue, and credit facilities
DCW	DCM	Daily	Providing vegetable price information and paying rental fees

Table 4
Network metrics for stakeholders in the TVSC.

Stakeholders in the TVSC	Network Metrics		
	Degree Centrality	Betweenness Centrality	Closeness Centrality
Government Agriculture Policy Institute (GAPI)	0.375	0.000*	0.000*
Agriculture Input Regulatory Authority (AIRA)	0.250	0.036	0.125
Farming Input Suppliers (FIS)	0.500	0.125	0.167
Authorized Sellers (AS)	0.250	0.036	0.188
Agriculture Field Officer (AFO)	0.500	0.125	0.281
Farmer Societies (FS)	0.125	0.000*	0.250
Farmers (F)	0.375	0.125	0.347
Distribution Center Wholesalers (DCW)	0.250	0.053	0.300
Distribution Center Manager (DCM)	0.375	0.000*	0.4711

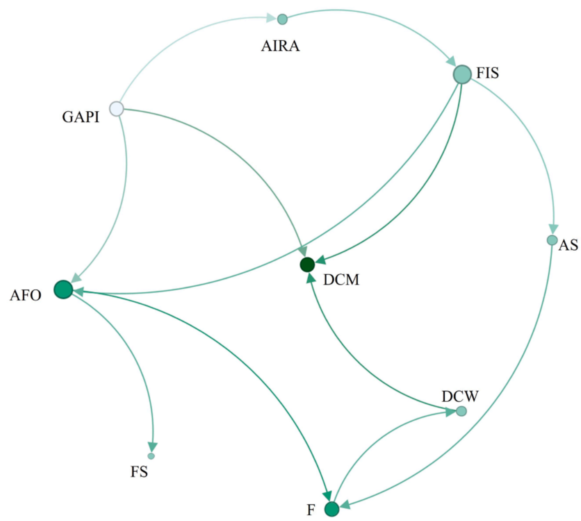

Fig. 6. Social network diagram.

regulating agricultural inputs through the AIRA will lead to reduced post-harvest loss, ensure product availability at reasonable prices in the free market, and equitable profit sharing among stakeholders. The GAPI and AIRA have to play critical roles in setting and enforcing policy frameworks to ensure this system. Further, increased transparency is essential, with AFOs guiding farmers and DCMs ensuring efficient market operations and communication.

4. Results and discussion

4.1. Digitalized architecture integrating regulated seed management

Currently, in the TVSC of developing economies, the process of collecting essential information and data is entirely manual. In the case study country, AFOs are responsible for periodic visits to farmers' land, and their primary tasks include gathering necessary information and data and providing essential agricultural advice to ensure optimal crop yields. The information typically encompasses details about farmers, land specifications, crop particulars, and information related to farmer associations. AFOs are responsible for the collection and subsequent communication of this data to the relevant GAPIs. However, the existing manual process faces critical challenges. Firstly, the GAPIs cannot capture this information in real-time, leading to delays and uncertainty regarding its accuracy. Several factors contribute to these challenges, including the discrete nature of small-scale farmer locations, limited access to these remote areas due to the high number of farmers assigned to each AFO, and the low digital literacy of the farming community. Additionally, limited access to internet connectivity in rural regions further complicates the problem.

In the distribution and marketing phases of the supply chain, numerous stakeholders are involved through DECs located in major cities across the case study country. Nevertheless, there are several challenges that persist in collecting information and data related to the trading and distribution processes. Presently, administrative officials at the DECs primarily record pricing information for the various vegetables sold on their premises. Nevertheless, their roles are largely restricted to regulating the infrastructure of the DECs, and they are not actively involved in overseeing distribution and marketing operations due to challenges such as the informal monopoly among wholesalers and political interventions. This disconnect poses a significant obstacle to the digital transformation process in the case study country.

To address these issues and drive the digital transformation process through digitization and digitalization, we have developed a digitalization architecture as depicted in Fig. 7 with the objective of optimizing the TVSC through a sustainable regulated digitalization framework.

This data collection architecture aims to enhance the efficiency of information collection and optimize the resource use in the supply chain, starting from the initial point of the supply chain, which is the agri-input suppliers. The key objective is to improve the visibility and transparency of the supply chain compared to the traditional manual processes and bring data-driven decision-making to optimize the resource use along the supply chain network while reducing post-harvest loss by minimizing excess harvest through seed distribution. Since a cold chain is not available in the TVSCs in most developing economies, this strategy will be the first step towards sustainable digital transformation.

The data collection process commences at the agri-seed supplier level, where AIRA creates user profiles for FIS and AS, assigning each user a unique national identifier, such as the Business Registration Number (BRN) or the Taxpayer Identification Number (TIN), as per the 2nd row of Fig. 7. Through this, a new seed supplier can be added to the system, where they are registered and categorized alongside existing seed suppliers. Similar to FIS, new farmer communities with farmers are registered and integrated with existing ones using the National Identity Card Number (NICN) or TIN by the relevant AFOs as per the 5th row of Fig. 7. AFOs are responsible for creating and updating farmer profiles, land information, crop data, and harvest records, which are linked to unique IDs to ensure consistency and traceability.

Through this data collection procedure, the Central Agri Information Platform in the 3rd row, as per Fig. 7, will be enabled to act as a repository for profiles and information of farmers, farmer communities, FIS and AS with seed information, land profiles, crop profiles and harvest profiles. The platform allows for the updating of land, crop, and harvest information, ensuring accurate and timely data collection by integrating the farmer with AFO, agri-seed suppliers and authorized sellers.

In the distribution and marketing stage at DECs, new and existing wholesalers are registered on the platform by DCM as per the 7th row of Fig. 7. It will enable DCM to update wholesale prices based on current market conditions while overseeing the creation and updating of wholesaler profiles. It ensures that wholesale prices are regularly updated to reflect market dynamics. This integrated digitalized system will allow GAPI to generate reports that include detailed information on farmer land, crop details, harvest details, seed supplier, distribution details, wholesaler details, product buying and selling prices as per the 2nd row of Fig. 7. Thus, GAPI can develop a national crop management schedule by analyzing the supply and demand of the TVSC, considering the overall market supply and the wholesale prices. Thereby, GAPI can regulate the FIS and AS to distribute the seeds according to the crop management schedule with the support of farmer communities and the AFOs. GAPI can use this digitalized platform as a regulatory framework to transform the TVSC into a sustainable TVSC with optimized resource use by technology integration. The framework can act as a decision support system to regulate and manage the entire agricultural supply chain, from seed distribution to harvest management, ensuring that supply closely matches demand with the required mathematical modelling to forecast accurately with minimal uncertainty. Hence, this digitalized architecture could be used to optimize crop production through seed regulation, which would result in reduced waste and stabilized market prices, benefiting both farmers and consumers.

4.2. Cross verification of architecture by benefit triangulation

The data management system for the vegetable supply chain in the country in the case study holds significant potential for revolutionizing the agricultural sector. A practical approach to data cross-validation is necessary to ensure the accuracy and reliability of the recorded data within this system. This process involves multiple entities collaborating to verify and validate the data, thereby enhancing the integrity of the information and fostering a more robust agricultural ecosystem. This

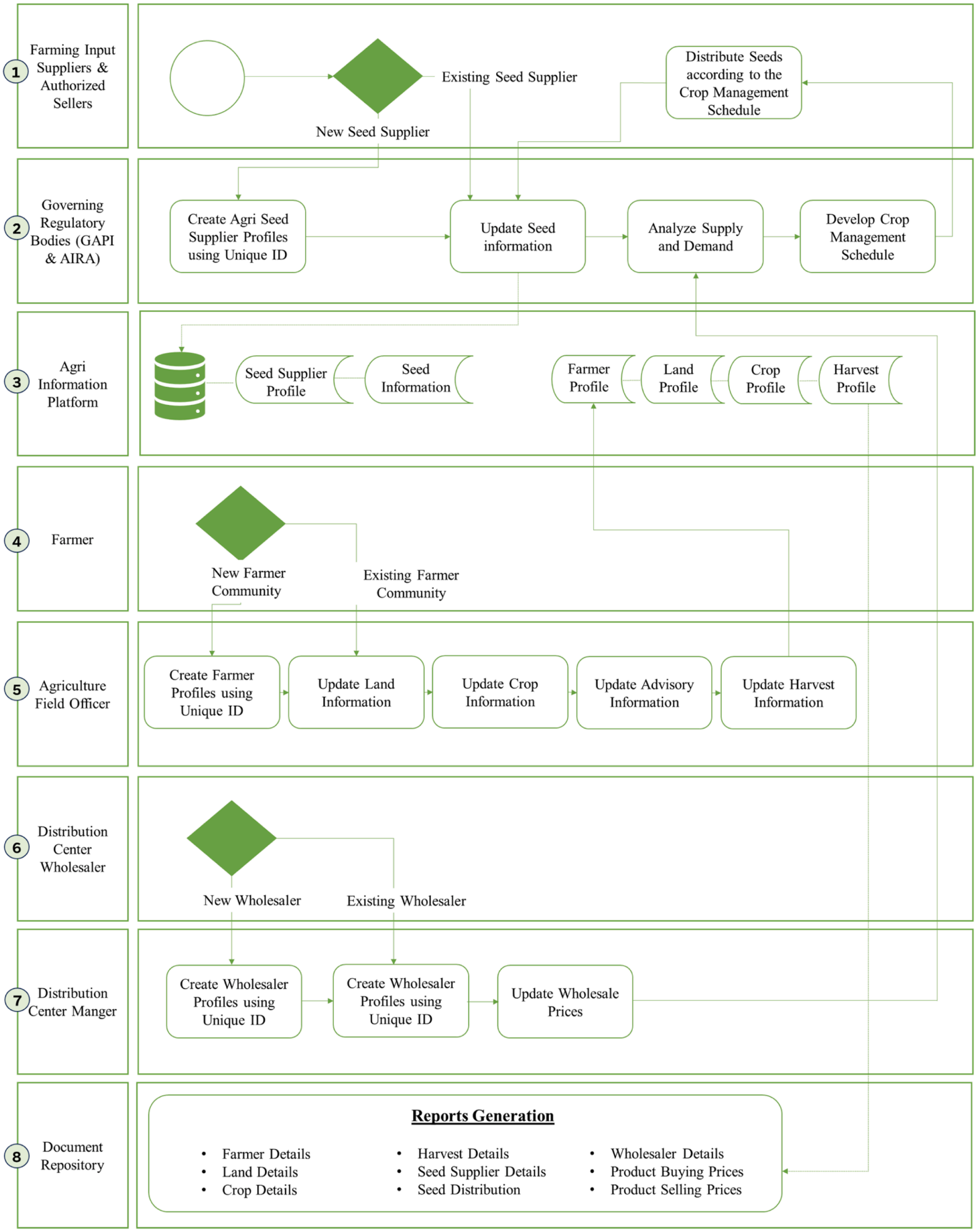

Fig. 7. Proposed digitalization architecture.

approach acts as a robust strategy to mitigate the risk of errors or inaccuracies associated with relying solely on a single data source through triangulation. By cross-verification from diverse angles, stakeholders can enhance the credibility and confidence in the accuracy of their data. In the context of cross-verification, triangulation validates the data and improves the accuracy of the collected data. The validation of this data is essential and can be accomplished through triangulation of benefits in a practical context as per Fig. 8.

1. **FIS and AFO** - FIS can collaborate with the AFO to verify the farming inputs provided to farmers, ensuring that the right products reach the appropriate beneficiaries. In return, FIS can benefit from marketing opportunities for their inputs through the AFO's trusted channels within the farming community. This partnership allows FIS to gain credibility and increase sales. In exchange, the AFO provides accurate farmer information, which allows FIS to target the right farmers based on their needs, boosting the efficiency of input distribution. By maintaining accurate data, both parties benefit from streamlined

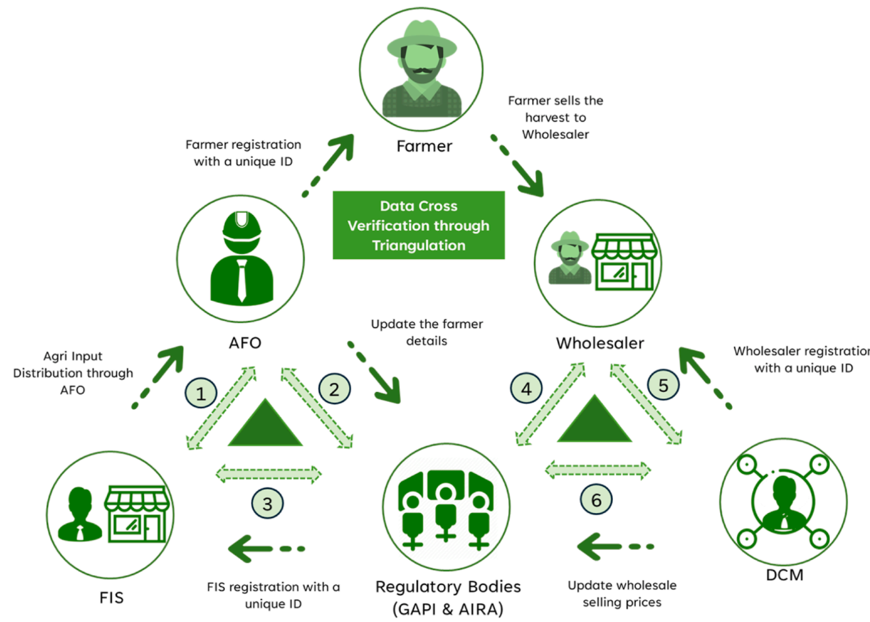

Fig. 8. User data validation backbone of the architecture.

operations, improving trust and transparency in the agri-supply chain.

2. **AFO and Regulatory Bodies** - Regulatory bodies benefit from the accurate, on-the-ground data provided by the AFO. The regulatory bodies can track the number of farmers covered and use this information to allocate resources effectively. In return, regulatory bodies can offer performance-based incentives to AFOs, such as bonuses or awards for covering a significant number of farmers and ensuring that the data provided is accurate and up-to-date.
3. **FIS and Regulatory Bodies** - FIS can report the distribution of farming inputs to regulatory bodies, allowing for real-time tracking of input distribution at the farm level. This provides regulatory bodies with essential data for monitoring the effectiveness of input programs and identifying areas for improvement. In return, regulatory bodies can offer tax concessions or other fiscal incentives to FIS for their role in supporting sustainable agricultural practices. These concessions not only reduce FIS's operational costs but also encourage compliance and transparency in input distribution, ensuring that farming communities benefit from proper access to resources.
4. **Wholesaler and Regulatory Bodies** - Regulatory bodies should play a significant role in acquiring and analyzing pricing, supply and demand data generated during the vegetable buying and selling process. They are responsible for providing accurate forecasting and making relevant policy decisions to manage the vegetable supply chain. Hence, regulatory bodies can offer tax concessions for wholesalers to encourage transparent transactions while contributing equitable profit sharing to the farming community. In order to maintain this sustainability, regulatory bodies can collect a fair amount of taxes from wholesalers while converting that tax into providing financial subsidies to support the farmer community.
5. **Wholesaler and DCM** - Identifying and verifying the wholesaler's total profit becomes a crucial aspect of the DCM. This can be achieved by implementing a policy between the DCM and the wholesaler. According to this policy, the wholesaler should receive the necessary facilities facilitated by the DEC premises. The DEC manager is then responsible for providing these facilities, easing the wholesaler's business operations. On the other side, the DEC will collect a commission payment as a percentage of the wholesaler's total profit in return for the facilities provided. Importantly, this commission payment should be fair and not adversely impact the pricing of vegetables.
6. **Regulatory Bodies and DCM -** DCMs can be compelled to maintain accurate records of transactions occurring within the DEC premises. This responsibility can be compensated by providing a performance-based increment to the administration staff based on the revenue collected within the DEC. Through this, regulatory bodies gain better access to a wider community engaged in the agriculture industry through real-time updates in a comprehensive and regularly updated database.

4.3. Architecture impact

When assessing the current state and envisioning the future of the agricultural supply chain, it is crucial to scrutinize scopes across planning, farming inputs, production, logistics, markets, and financial services. These scopes serve as vital touchpoints in ensuring the efficiency and sustainability of the supply chain. In the strategic blueprint for revolutionizing the agricultural sector via digitalization, we must navigate several pivotal phases, encompassing cultivation planning, farming inputs, production, logistics, markets, and financial services, as, Manzano & Pérez [48] recommend. By addressing the challenges inherent in these stages of the agricultural chain, we can develop an entirely new ecosystem that harnesses technology's potential to deliver products and services, ultimately enhancing performance, efficiency, and profitability for all stakeholders within the agricultural value chain [49]. Fig. 9 provides a concise visualization of the transformation from the current "As-Is" state practices, characterized by existing inefficiencies and waste in the supply chain, to the envisioned "To-Be" state practices, illustrating the value propositions made through digitalization.

In the context of planning, the sources of agronomic information play a pivotal role, as per the study conducted by Shukla et al. [50]. In the current state, the case study country's TVSC relies heavily on manual data collection methods, hindering efficient decision-making. However, in the envisioned "To-Be" state, the proposed data management system promises real-time access to agrarian and agronomic information, empowering farmers with up-to-date insights ensuring sustainable development and crop management [34–51]. Decisions on seed and fertilizer imports and management are equally significant. In the present supply chain, these decisions are often made with limited information

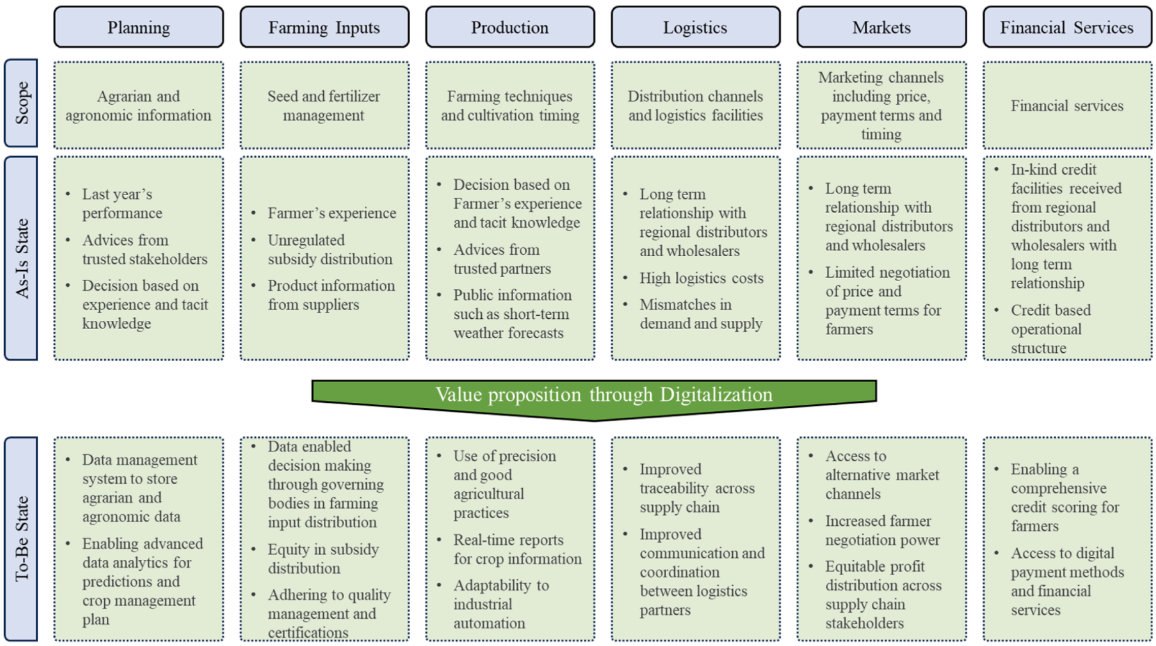

Fig. 9. Comparison of As-Is and To-Be states.

and coordination. Conversely, the "To-Be" state leverages data-driven insights to optimize seed selection and management, ultimately leading to improved crop yields. As Jarial [43] suggested, this study proves that crop protection and farm inputs distribution and management decisions can be enhanced through the proposed system in this study. By centralizing data, stakeholders can make informed choices, ensuring the judicious use of pesticides and fertilizers. Additionally, at the production stage, decisions on farm techniques and cultivation timing are facilitated by real-time weather data, fostering more efficient and sustainable practices compared to the current state.

The availability of distribution channels and storage facilities plays a crucial role in both states. In the current scenario, limitations exist in channel accessibility and storage capacity. However, the "To-Be" state introduces streamlined distribution and improved storage options, reducing post-harvest losses and ensuring produce quality through improved stakeholder communication and coordination. Decisions regarding selling channels, pricing, payment terms, and timing are refined in the "To-Be" state, with greater transparency and data-driven insights. Furthermore, broader access to financing for farmers becomes a reality, addressing a significant barrier to growth in the current supply chain.

Comparing the "As-Is" state with the "To-Be" state, the transformation is evident. The TVSCs in the case study country should evolve from a manual, fragmented, and information-starved system to a digitally empowered, data-driven, and transparent ecosystem. The future state not only streamlines operations but also places farmers at the center of decision-making, offering them the tools and knowledge needed for sustainable and profitable agricultural practices. In this envisioned state, the vegetable supply chain in the case study country can emerge as a model of efficiency and innovation, poised for continuous improvement and growth.

5. Conclusion

This study on digitalizing the TVSC has laid the foundation for a transformative journey toward a more efficient and sustainable agricultural ecosystem. The study includes a methodically crafted research design through an As-Is state analysis by process mapping and a stakeholder analysis using SNA. This research design allowed us to seek the answers to two research questions identified in the study. The research primarily focuses on identifying current bottlenecks and influencing factors that hinder the streamlining of information silos in traditional vegetable supply chains within developing economies, as well as on developing a centralized and digitalized system that aggregates and enhances interaction among these supply chains to minimize waste.

The As-Is analysis highlights the fragmented information flow, lack of real-time data sharing, and limited stakeholder coordination as current bottlenecks with the TVSC. As per the results of the SNA analysis, we identified stakeholders with the highest connectivity and the strategic position to influence and control the supply chain. Considering these results, a robust data collection and decision support architecture was developed to shift from the manual, paper-based methods of the As-Is state. It converts the existing manual data collection state to a digitized system as the initial step of digital transformation, which is the conversion of analog information into digital form. The developed architecture is able to streamline the information flow through data analytics, and it empowers stakeholders of the supply chain by transforming the existing system into a digitalized system as the second step of the digital transformation process. Adding to that, this architecture can be used as a regulated framework to manage seed distribution, which ensures the sustainable behaviour of the supply chain by matching the harvest supply with the demand. This minimizes postharvest losses caused by excess supply, which contributes to sustainable performance. The architecture impact assessment has provided indications of the positive changes that digitalization can bring, from enhancing efficiency in cultivation planning to ensuring transparent financial transactions.

This transition promises a multitude of advantages, including improved decision-making in cultivation, optimized resource allocation, reduced post-harvest losses, and expanded market access. This study established a foundation for the digitalization of agri-food supply chains in developing economies, as illustrated in Fig. 10, with the goal of achieving digital transformation. The roadmap for developing a digitalized agri-food supply requires further studies, including a technical study, a financial study, a socio-economic study, a regulatory study and empirical validation. Embracing digitalization unlocks the full potential of TVSC in developing economies, benefiting farmers, consumers, and entire agricultural ecosystems. However, there can be potential drawbacks, uncertainties, or unintended consequences that may arise during the implementation of the framework. Therefore, further studies should be conducted on how to address the digital transformation barriers such

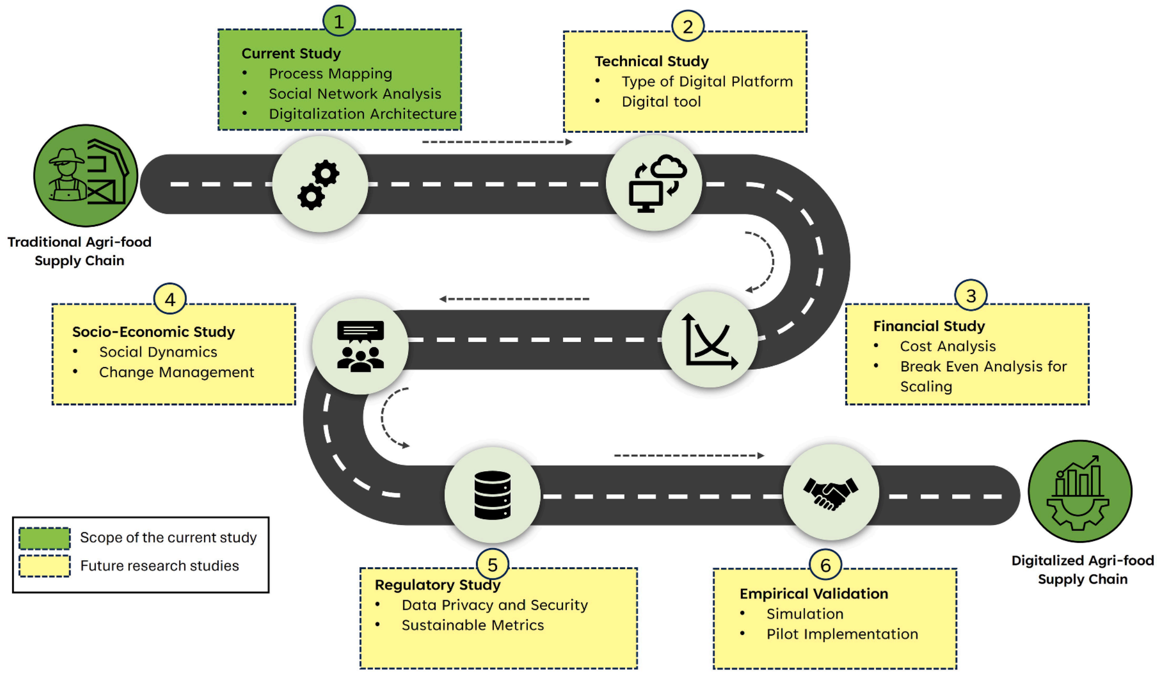

Fig. 10. Progression toward digitalization.

as limited digital infrastructure, traditional mindsets that resist digital transformation, financial constraints, limited digital literacy, digital divide, data security and privacy concerns.

CRediT authorship contribution statement

Madushan Madhava Jayalath: Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **R.M. Chandima Ratnayake:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition. **H. Niles Perera:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Amila Thibbotuwawa:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Madushan Madhava Jayalath reports financial support was provided by Norwegian Agency for Development Cooperation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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