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Viable Agri-Food Supply Chains: Survival Through Systemic Adaptations

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Abstract

Ensuring the continuous supply and availability of food during long-term disruptions remains a critical challenge for agri-food supply chains (ASCs). Traditional resilience strategies, which focus on short-term recovery, often fall short during prolonged or systemic crises. This study examines how ASCs adapted during the COVID-19 pandemic, demonstrating that sustained food access was achieved through systemic adaptations that moved beyond resilience to a more enduring state of viability. Using qualitative data from interviews and focus group discussions across urban, semi-urban, and rural regions (spatial ecologies), the study explores event-level adaptations made by stakeholders within production, logistics, and consumption segments of the agri-food channels. To explain consumer decision-making when switching between ASC channels, a four-mode ASC classification (M1–M4) and a Cost–Availability–Quality (CAQ) framework were developed. Here, a channel represents a distinct route through which fresh agri-food products flow from producers to consumers. Behaviour Over Time (BOT) graphs illustrate how channel usage evolved before, during, and after disruption. Findings reveal that viability was achieved through interconnected adaptations shaped by spatial context and enabled by digital tools, community networks, and policy support. The study provides a structured foundation for understanding ASC viability through real-world adaptation and offers a basis for future systems-modelling research.

Keywords: agri-food supply chains (ASCs); viability; disruption(s); adaptation(s); resilience; food security; enabling factors; systems modelling; COVID-19 pandemic; spatial ecologies

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1. Introduction

Maintaining an uninterrupted food supply and availability is one of the most pressing challenges faced by agri-food supply chains (ASCs) during long-term disruptions. The COVID-19 pandemic, as a prolonged and systemic crisis, exposed the limitations of conventional resilience approaches that primarily focused on short-term recovery to a pre-disruption state. This paper introduces *viability* as the enduring ability of ASCs to adapt and survive under long-term disruptions. Such adaptations were shaped by enabling factors, including digital readiness, community networks, and policy interventions. By grounding the concept of viability in real-world adaptations, this study lays a foundation for future systems-level research.

ASCs are essential to ensuring the availability, affordability, and quality of food, a basic, non-negotiable need. Yet, they are inherently vulnerable due to the perishability of products, seasonal production cycles, weather sensitivity, and the complexity of actor networks and infrastructure. These factors complicate coordination, particularly during crises, and hinder the alignment of supply with demand and the efficient movement of food from production to consumption. The COVID-19 pandemic made these weaknesses highly visible, with rising prices, empty shelves, and compromised quality [1] stemming largely from logistical breakdowns [2]. International organisations such as the Food and Agriculture Organisation (FAO) of the United Nations warned of escalating food insecurity, calling for systemic transformation of food systems [3].

Despite widespread disruptions, communities across different regions demonstrated diverse adaptive strategies to secure food. These ranged from vertical farming in Singapore [4], home gardening in Sri Lanka, Malaysia [5], and Japan [6]; food hubs in the USA [7]; to online ordering platforms in multiple countries. Such adaptations occurred at different stages of the supply chain: production (cultivation to harvesting), logistics (collection, processing, storage, and transport), and consumption (purchasing, last-mile delivery, and final use) [8,9]. Collectively, they introduced alternative practices that reshaped traditional supply channels, creating new structures for sustaining food flows during crises.

To explain these dynamics, this study applies the concept of viability, an evolution beyond resilience [10]. Whereas resilience typically implies "bouncing back" within a single supply chain, viability emphasises "bouncing forward and adapting" at the ecosystem level. It is defined as the capacity of supply chains to sustain themselves in changing environments through structural and performance adaptations [11]. Achieving viability requires coordination among multiple stakeholders and is increasingly supported by digital technologies. While extensively examined in manufacturing and services [12–14], viability remains underexplored in ASCs [15,16]. Filling this gap is critical, given the FAO's emphasis on cohesive policies to ensure the availability of safe, affordable, and nutritious food [3].

This study addresses this gap by investigating ASC adaptations that occurred across diverse spatial areas during the COVID-19 pandemic and subsequent crises. These multiple disruptions created an ideal setting to examine how ASC structures were disaggregated and reorganised to maintain food flows. Using stakeholder interviews and focus group discussions, the study explores the dynamics of adaptation, focusing on the reorganisation of ASC actors and the enabling factors that supported such changes.

The study's contributions are threefold. First, it develops a four-mode classification (M1–M4) of ASC channels and introduces the Cost–Availability–Quality (CAQ) framework to analyse consumer decision-making during disruptions. Second, it examines how consumers transitioned between emerging channels across spatial ecologies. Third, it identifies the key system-level enablers that shaped ASC adaptations during crises.

Findings reveal that ASC viability was achieved through dynamic adaptations: consumers altered their sourcing strategies while supply chains reorganised to reconnect production and consumption when traditional channels failed. These insights establish a structured understanding of ASC viability grounded in empirical evidence and provide a foundation for future systems modelling and policy-oriented research.

2. Literature Review

Every system functions differently under normal and disruptive conditions, and so do supply chains. This review contrasts how agri-food supply chains (ASCs) operate in normal, disruptive, and long-term disruptive contexts (e.g., COVID-19), and positions viability within the ASC domain.

2.1. Agri-Food Supply Chains (ASCs) Under Normal Conditions

2.1.1. ASC Definition

A supply chain is a series of interconnected processes and entities that move products from production to consumption [17]. In the case of agri-food, these supply chains form multi-actor networks that deliver farm products through various stages, including production, processing, testing, packaging, warehousing, transportation, distribution, and marketing [18]. Due to multi-stakeholder interdependencies, ASCs function as complex networks rather than linear chains [19]. They are especially volatile due to perishability, seasonality, and weather sensitivity [19], which increases susceptibility to disruption.

2.1.2. ASC Classifications

Since this study aims to identify and organise agri-food supply chain (ASC) adaptations, it is essential to first understand the various ways ASCs have been classified in prior research. Different classification frameworks provide lenses through which adaptations can be grouped and analysed later. Scholars have categorised ASCs based on multiple criteria (Refer to Table 1):

Table 1. Agri-food supply chain classification.

Classification Basis	Classification	Description/Examples		
By product type [20,21]	Fresh Products	Key characteristics include complex supply chains, perishability, and need for cold chains, e.g., fruits, and vegetables.		
	Processed Products	Canned foods and desserts.		
By the degree of consumer engagement [22]	Minimal consumer engagement	Box schemes, farmers' markets.		
	Collaborative models	Community-supported agriculture, consumer cooperatives, and participatory guarantee systems.		
By the supply chain structure	Temporal arrangement [23]	Refers to the timing of different components in the supply chain.		
	Vertical stratification [23]	Describes the hierarchical levels of the various components.		
	Spatial arrangement	Refers to the geographical location and distribution of elements within the supply chain.		
		Long (Conventional) Food Supply Chains [24] [25]	Long food supply chains involve more intermediaries, leading to greater spatial distances between producers and consumers.	
		Short Food supply chains [25]	Face-to-face [25]	Supply chains, where consumers purchase directly from producers
			Spatially proximate	Products are sold through local outlets in the area, and consumers are immediately aware of their local nature.
			Spatially extended	Supply chains, such as those that export.

By product type: fresh (perishable, cold chain intensive, e.g., fruits and vegetables) versus processed (e.g., canned foods) [20,21].

By degree of consumer engagement: minimal (box schemes, farmers' markets) to collaborative (community-supported agriculture, consumer co-ops, participatory guarantee systems) [22].

By structure: temporal arrangement (timing), vertical stratification (hierarchy), and spatial arrangement (geography) [23]. Spatially, long or conventional chains span many intermediaries and distances, whereas short chains include face-to-face, spatially proximate (local outlets), and spatially extended (export-oriented) formats [24,25].

These are the types of channels that supply food to consumers, enabling the movement of agri-food from farmer to consumer, ensuring food availability in sufficient quantities at affordable prices, which are essential components of food security [26]. Their prominence and accessibility vary by geography and socio-economic context, affecting performance under disruption.

2.2. Agri-Food Supply Chains Under Disruptive Conditions

Recent years have brought significant and enduring ASC disruptions [27], including COVID-19, the Russia–Ukraine war, and regional conflicts [28,29], which constrained consumer access to fresh produce and aggravated food insecurity [2,30].

2.2.1. Disruptions

Across definitions, a disruption is an unintended event or transition from a planned to an unplanned state that significantly degrades performance and cannot be managed without additional control efforts; it may originate anywhere in the supply chain or its environment [31–33]. Typical triggers include transport delays, port stoppages, natural disasters, quality issues, operational failures, and terrorism [34]. In all cases, disruptions depress performance, sometimes sharply.

2.2.2. Performance Dynamics During Disruptions

Supply chain performance typically traverses through several phases (Refer to Figure 1 adapted from Bukowski [35] and Sheffi and Rice Jr [36]): Bukowski [35] explains these fluctuations through a systemic view (Four Phases of Disruption), while Sheffi and Rice Jr [36] describe them from an enterprise view (Eight Stages of Disruption), both providing performance curves of similar shapes. Figure 1 presents an integrated diagram of the two curves, illustrating how they overlap and complement each other to depict the dynamic process of performance degradation, recovery, and adaptation. These phases are outlined under the four main phases identified by Bukowski [35]:

(I) Robustness/resistance (absorbing routine disturbances);
(II) Shock and survival (performance drop then stabilisation at a survivable level);
(III) Resilience (recovery to an acceptable level within a recovery time);
(IV) Adaptation (learning and structural change, potentially exceeding pre-disruption performance or prompting re-engineering if adaptation fails).

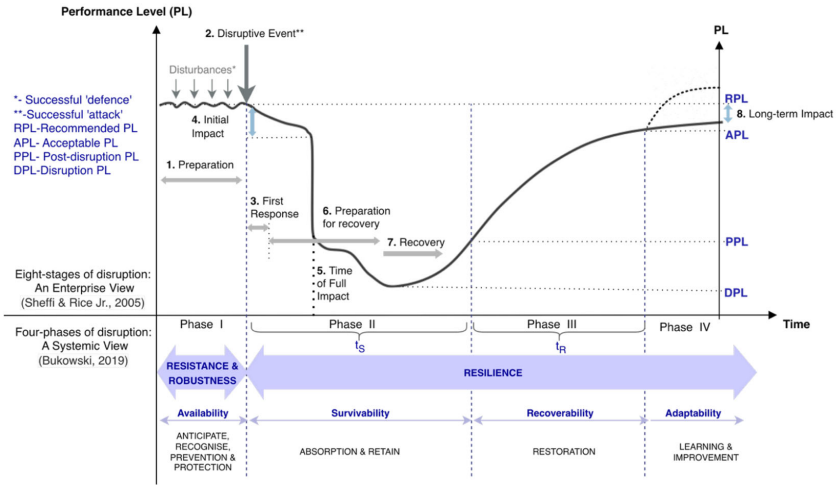


Figure 1. Impact of disruption on supply chain performance over time. Adapted from Bukowski [35] and Sheffi and Rice Jr [36].

Integrating Bukowski's systemic perspective with Sheffi's enterprise view shows that resilience enables short-term recovery, while adaptation secures long-term continuity improvement. For agri-food supply chains exposed to recurrent shocks such as pandemics or climate-related extremes, sustained performance depends on continuous learning, reconfiguration, and transformation beyond immediate restoration. Performance deviation itself triggers recovery responses whose scale depends on disruption severity and preparedness across supply, demand, process, and structure of the supply chain [37,38].

2.2.3. COVID-19 as a Super Disruption

COVID-19 simultaneously disrupted ASCs from multiple angles: supply, demand, processes, and structures (Refer to Table 2), producing price spikes, empty shelves, and quality concerns [2,27,39].

Table 2. COVID-19 disruption impact on ASCs.

ASC Process Disrupted	Challenge	Initiatives/Recovery Strategies	Areas Impacted by Initiatives			
			Demand	Supply	Process	Structure
Farm production	Labour shortage; bottlenecks in other inputs	-Robotisation: information-driven independent choices in production.		x	x	
Food processing	Food security and protection of employees	-Employees' safety and health, change in working conditions: sanitisation, monitoring and screening the workers, cleaning and disinfecting the facilities, etc. -Additional food preparation facilities.		x	x	x
	Labour shortage, prevention of the transportation of microorganisms by people	-Efficiency improvement initiatives for physical distancing during production, such as robotisation. -Direct sales through digital platforms. -Selling meal kits rather than prepared food.		x	x	x

Table 2. *Cont.*

ASC Process Disrupted	Challenge	Initiatives/Recovery Strategies	Areas Impacted by Initiatives			
			Demand	Supply	Process	Structure
Logistics	Logistical barriers due to the lockdown	-Buyer chooses takeaway and home delivery because of social distancing and the shutdown of restaurants. -Click and collect method. -Linking farmers and restaurants directly to food banks.		x	x	x
	Collection and distribution of agri-food to consumers	-Urban distribution centres improve the effectiveness of the transportation and collection process.			x	x
	To secure food delivery to people from weaker sections at a reasonable cost, especially the main ingredients	-The Public Distribution System (PDS) is used to access the weaker segments.			x	x
Demand	Enabling a quicker and adaptable joint effort among organisations and consumers	-Internet-based supply chain systems.	x	x	x	x

Key: 'x' denotes the respective impacted area of the agri-food supply chain. Source: Compiled based on Organisation for Economic Co-operation and Development [2]. Barman, Das and De [39], Savary, Akter, Almekinders, Harris, Korsten, Rötter, Waddington and Watson [27] the researchers' understanding.

Unlike "instantaneous" shocks (e.g., earthquakes or fires), pandemics are super-disruptions [40,41]. Instantaneous disruptions cause immediate, short-term impacts, typically confined to a single supply chain echelon, with recovery beginning once the event ends. In contrast, super disruptions such as pandemics have long-lasting, unpredictable effects that simultaneously impact supply, demand, and logistics across multiple echelons. Recovery during such events occurs amid ongoing disruption, involving overlapping closures and reopenings of suppliers, facilities, and markets. Since COVID-19 affected all these areas, it represents a unique super disruption that compelled supply chains to adapt continuously.

2.2.4. Adaptations During COVID-19: Mapping ASC Responses to Viability Strategies

(a) Insights from the manufacturing and services sectors

After examining how major manufacturing supply chains responded to the COVID-19 pandemic, the adaptation strategies can be generalised into four categories: intertwining, substitution, scalability, and repurposing [12,42]. These strategies are generally defined as follows:

Intertwining involves collaborations across supply chains and industries. Examples from manufacturing include ALDI and McDonald's sharing workforces, or Amazon partnering with Lyft to fill logistics roles, demonstrating how partnerships sustain continuity under labour shortages [42].

Substitution reflects the creation of alternative sourcing or market channels, as seen when European manufacturers regionalised their supply bases or food businesses, such as Fuddruckers, redirected existing capacity to household goods [42].

Scalability refers to the ability to adjust capacity to handle surging demand; Amazon's rapid expansion of its logistics network exemplifies how flexible capacity safeguarded access during uncertainty [42].

Repurposing is the redeployment of idle assets, such as Ford and Tesla converting automotive production lines to manufacture ventilators and protective equipment, or UK F1 teams engineering medical devices [12].

Collectively, these examples highlight how viability during disruption arises from collaborative, flexible, and reconfigurable system behaviours that realign resources across sectors to sustain essential flows.

Adaptation in manufacturing and across various sectors demonstrated a crucial need for agility and resilience in supply chains. A key enabling attribute is the use of collaborative strategies, such as intertwining, which proved necessary for addressing shared challenges, including sourcing difficulties and labour shortages [43]. Furthermore, digitalisation has emerged as a key enabler of supply chain visibility, data-driven decision-making, and operational continuity [44]. For resilient supply chains, particularly highlighted in the pharmaceutical sector, ambidexterity is essential [14]. This concept involves balancing efficiency with flexibility, allowing companies to be cost-efficient by optimising current operations while simultaneously remaining adaptable and exploring new possibilities in response to changing circumstances [14]. Given the complexity of modern disruptions, adaptation often relies on hybrid approaches, which are multifaceted and combine various strategies [45]. An example of a successful hybrid approach is Ford's production of ventilators, which combined attributes such as repurposing, intertwining (specifically with 3M), and utilising potential scalability [12,42].

The above-mentioned examples mainly originate from manufacturing supply chains, while a few are from service sectors such as restaurants and e-commerce. However, it includes grocery retailers, which may encompass fresh food, though not exclusively. Thus, there are few or no examples from agri-food supply chains. Can these strategies be applied to agri-food supply chains, and what developments have occurred in this area? These are the critical questions. However, these strategies have not been explicitly reported in the existing literature on agri-food supply chains. The adaptations observed globally with respect to agri-food supply chains are presented below (b).

(b) Adaptations in ASCs

When studying how individuals secured fresh produce during disruptions, the existing literature mentions various ways consumers sourced fresh agri-food, which were frequently digitally enabled and included government intervention [5]. ASC adaptations spanned all stages: production (farming), logistics (farmer-to-retailer), and consumption (retailer-to-consumer) [8,9,46].

Production: Various production adaptations have emerged worldwide in response to food supply challenges during the COVID-19 pandemic. These include home gardening campaigns (e.g., Sri Lanka, Philippines, Fiji) [5]; vertical/urban farming (e.g., Singapore) using hydroponics/aeroponics and smart agriculture [4]; and social media-enabled farming knowledge sharing and communities [47], further empowering consumers to participate in farming activities.

Logistics: Logistics adaptations centred on strengthening local and regional food distribution through physical and virtual food hubs, which aggregate, market, and distribute products to wholesale, retail, and institutional buyers [7]. U.S. food hubs sustained or even improved profitability during the crisis by leveraging federal programs and building

new partnerships. Online platforms further enabled direct producer–consumer linkages through home deliveries, while passenger logistics firms such as Uber (India) and Bykea (Pakistan) pivoted into food delivery services [48]. Similarly, rapid delivery providers like Getir in Turkey supported small retailers with e-commerce and hyperlocal logistics solutions [48].

Consumption/retail: Consumers adapted by shifting to local farmers' markets, growing their own food, and increasingly using digital platforms to order fresh produce from supermarkets or farmers' markets [30]. Social media supported home gardening and food-sharing communities [47] while retailers expanded digital services such as click-and-collect and frequent home deliveries [49,50]. Community and peer provisioning also played a role in ensuring access, with digital tools enabling physical and virtual channels to co-exist and expand consumer accessibility.

Digital adaptations: The COVID-19 pandemic accelerated the adoption of digital technologies in agri-food supply chains, particularly in developing countries [48], to address challenges, and it enabled most of the adaptations discussed above. This shift significantly enhanced food availability in multiple ways.

Consumers increasingly relied on online platforms for food delivery, which increased accessibility to a variety of foods [48]. The pandemic further spurred the growth of online platforms that directly connect farmers with consumers, bypassing intermediaries [30,50]. This not only improved food availability but also provided consumers with fresher, more nutritious options [50]. With physical interactions restricted, digital platforms became crucial for disseminating information about food production and availability [51,52]. Consumers who turned to home gardening could easily access farming knowledge online through social media communities [47]. Farmers and other stakeholders could access information about market trends, government support programs, and best practices for safe food handling during the pandemic [51].

Classifying these ASC adaptations using the same four strategies of intertwining, substitution, scalability, and repurposing [42] clarifies the mechanisms (Table 3), even though prior ASC literature rarely framed them in this manner.

Table 3. Agri-food supply chain sector adaptations mapped to intertwining, substitution, scalability, and repurposing.

Production Adaptations	Logistics Adaptations	Consumption Adaptations
Strategy: Intertwining		
-Public–private partnerships for home gardening campaigns in Sri Lanka, the Philippines, and Fiji [5]. -Collaboration between urban farmers and technology providers for smart agriculture solutions in Singapore [4].	-Food hubs connecting local producers with consumers. -Virtual food hubs using digital platforms to link producers and consumers [7]. -Passenger logistics firms (Uber—India and Bykea—Pakistan) add food delivery services and maintain them afterwards [48].	-Retailers liaising with friends and families to deliver food. -Social media communities sharing information about home gardening and food availability. -Consumers rely on neighbours and community groups for food support in Australia [30].
Strategy: Substitution		
-Singapore shifting from imported food to locally produced alternatives [4]. -Replacing traditional farming methods with vertical farming techniques in Singapore [4].	-Shifting from supermarkets to local food hubs and farmers' markets [7]. -Replacing traditional distribution channels with online platforms and delivery services [7].	-Consumers shifting from supermarkets to local food sources and direct-from-farm purchases [30,50,53]. -Ordering fresh produce from online markets instead of physical stores [48].

Table 3. *Cont.*

Production Adaptations	Logistics Adaptations	Consumption Adaptations
Strategy: Scalability		
-Scaling up local food production through home gardening initiatives in Asian economies [5]. -Expanding vertical farming operations to meet growing urban food demand in Singapore [4].	-Food hubs aggregating products from multiple producers to meet larger orders. -Virtual food hubs scaling operations to handle increased online orders. [7]. -Rapid delivery services like Getir in Turkey establishing divisions to assist small retailers with e-commerce applications and logistics for hyperlocal delivery [48].	-Retailers expanding online presence and order processing capacity. -Supermarkets and farmer markets increasing delivery capabilities.
Strategy: Repurposing		
-Repurposing urban spaces for urban farming initiatives in Singapore [4]. -Utilising digital technologies to facilitate home gardening and knowledge sharing in Malaysia [47].	-Utilising existing infrastructure such as warehouses or community spaces for food hubs. -Adapting existing passenger transportation networks and logistics networks for food delivery services [3,7].	-Using social media platforms for disseminating information about food availability and gardening tips. -Retailers adapting in-store pickup options for online orders.

Note: the key adaptation strategies are indicated in bold subheadings

Comparison with manufacturing: While both manufacturing and agri-food supply chains adopted similar strategies of intertwining, substitution, scalability, and repurposing, digital adaptations were especially prominent across both sectors. Yet their drivers diverged: manufacturing focused on efficiency, cost, and continuity, whereas ASCs emphasised food security, sustainability, localism, and community networks. Agri-food adaptations further relied on informal actors, lean infrastructure, and behavioural shifts such as home gardening and urban farming, which uniquely enabled prosumption where households both produced and consumed food [54–56].

These adaptations strengthened food availability by reshaping both physical food flows and information flows. Altered information flows, mostly enabled by digital adaptations, shaped stakeholder decision-making and facilitated multiple adaptations. Together, these changes highlight the concept of "supply chain viability", the capacity to withstand long-term disruptions, which is explored further in Section 2.3.

2.3. Emergence of Supply Chain Viability

2.3.1. Definition of Supply Chain Viability

Supply chain viability (SCV) is a relatively new concept in supply chain management, defined as the ability of a supply chain to sustain itself and adapt in a changing environment [10,12,41,42,57]. Pre-COVID definitions framed viability as survival and redesign after disruption [38]. Subsequent work defined it as sustaining operations through structural and performance adaptations under long-term impacts, extending resilience's "bounce-back" to a "bounce-forward-and-adapt" ecosystem perspective [41,42,57]. Viability thus integrates economic and societal dimensions across intertwined networks, rather than focusing solely on individual chains [58].

2.3.2. Supply Chain Viability in Relation to Pre-2020 Strategic Paradigms

Supply chain strategies have progressed from lean (cost reduction) in the 1950s, to agile (responsiveness) in the 1990s, le-agile hybrids, resilience (post-2005), sustainability (post-

2010), and Industry 4.0 digitalisation (post-2015) [57]. While each optimised performance under bounded uncertainty, the COVID-19 pandemic exposed their limitations for managing prolonged, systemic disruption. This gap led to the emergence of viability (post-2020), which extends resilience by emphasising long-term adaptability, dynamic reconfiguration, cross-industry collaboration, and digitally enabled, ecosystem-level adaptation to establish a "new normal" [41,58].

Achieving this requires the system property of adaptability, which reflects medium-term behavioural and structural adjustments necessary for dynamic reconfiguration. Sustainability, on the other hand, emphasises a long-term balance across environmental, social, and economic dimensions. SCV rigorously distinguishes itself by combining short-, medium-, and long-term capacities through continuous processes of feedback, learning, and reconfiguration, thereby enabling supply chains to maintain their functionality and identity during prolonged and complex disruptions through structural and performance adaptations. Table 4 compares these four key system properties, distinguishing viability from each.

Table 4. Distinguishing supply chain viability, resilience, adaptability, and sustainability.

Concept	Core Focus	Temporal Orientation	System Response
Resilience [36]	Withstanding and recovering from short-term shocks or disruptions.	Short- to medium-term	Bounce-back to pre-disruption state.
Adaptability [59]	Adjusting structure and behaviour in response to changing conditions.	Medium-term	Modify processes or relationships to cope with change.
Sustainability [60]	Maintaining environmental, social, and economic balance.	Long-term	Balance and continuity without compromising future capacity.
Viability [57]	Ensuring long-term survival through continuous adaptation and structural reconfiguration under dynamic conditions.	Cross-temporal (short, medium, and long-term)	Bounce-forward and evolve through systemic design and feedback learning.

2.4. Agri-Food Supply Chain Viability

A clear definition of ASC viability in the existing literature is limited. However, ASC viability can be understood as the capacity of an agri-food supply chain network or ecosystem to ensure a consistent supply of safe and affordable food during long-term disruptions. This framing draws on the concept of supply chain viability [41,58] combined with the essential role of agri-food supply chains in achieving food security. Literature on ASC viability is still emergent [16,61,62]. Foundational work notes the scarcity of ASC-specific work [16], while empirical research is beginning to emerge (e.g., Lithuania during COVID-19 and the Ukraine war [62]).

2.4.1. Role of Digital Inter-Connection in ASCs for Viability

Digital interconnectivity strengthens information visibility and coordination, enabling real-time reconfiguration and better supply–demand alignment, while reducing waste and supporting multi-product logistics [63]. It also empowers consumers through access to agricultural and market information, allowing informed purchasing and prosumption via digital platforms [64]. Additionally, research and development play a pivotal role in establishing systems for planning, forecasting, and collaboration, while also creating new business opportunities in the agri-food domain [65,66]. Digitalisation supports

both informational and technological structures [38], enabling le-agility, resilience, and pandemic resistance [57]. In the post-pandemic context, Industry 5.0 emphasises a human-centred ecosystem perspective where supply chains maintain systemic balance under uncertainty [15,67,68]. Advanced technologies such as blockchain, IoT, big data, and AI further reinforce connectivity between partners and ensure preparedness for future disruptions [69].

2.4.2. Spatial Ecologies Within the ASC Ecosystem

Viewing ASCs as ecosystems across spatial ecologies (diverse geographic regions) highlights how ecological and spatial conditions shape processes, behaviours of actors, and outcomes [70]. Within the Viable Supply Chain (VSC) ecosystem thinking, ASCs interlink economic, social, ecological, and digital subsystems to optimise cost, quality, and availability in place-specific ways [70].

2.5. Summary and Research Gaps

This review *demonstrates* that traditional resilience strategies are *insufficient* for sustaining supply chains *during* prolonged disruptions. While the concept of viability highlights long-term *survivability*, its application to ASCs is still limited. Studies document adaptations across production, logistics, retail, payments, and consumption, often digitally enabled, but continue to prioritise conventional channel classifications. Emergent survival channels such as home gardening, community sharing, and informal networks remain underexplored despite their critical role in *supplying agri-food* during COVID-19. As a result, there is limited understanding of the enablers driving these adaptations, their variation across spatial ecologies, and the mechanisms through which they contribute to ASC viability. Addressing these gaps is essential for developing frameworks that integrate both formal and informal strategies to design food systems capable of withstanding long-term disruptions.

3. Methodology

3.1. Research Questions

Based on the identified research gaps, this study aims to address the following three research questions, which focus on understanding event-level adaptations made by ASC stakeholders and the factors influencing these changes.

RQ1: What ASC channels emerged to move food from production to consumption during COVID-19?

RQ2: How did spatial ecologies influence the choice of and transitions between channels and the role of cost, quality, and availability?

RQ3: Which system-level factors influenced the formation and adaptation of these channels?

3.2. Research Approach

This study employed a qualitative, empirical design to investigate how Sri Lankan ASCs adapted during prolonged disruptions (COVID-19 and subsequent crises). The focus was on observable adaptations reported by stakeholders and the factors that shaped those dynamics. Findings are presented as a narrative synthesis supported by structured analysis. Figure 2 illustrates the methodology followed in addressing the three research questions, which are explained in subsequent sections.

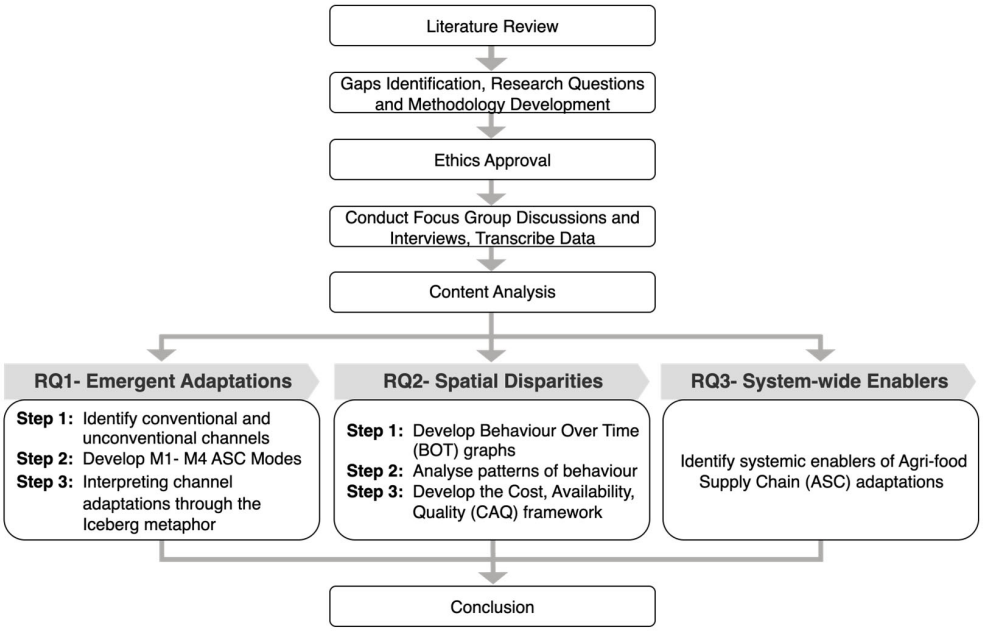


Figure 2. Methodology diagram.

3.3. Research Context

The study selected Sri Lanka as the research context because it experienced compounding disruptions, COVID-19 waves (2020–2021), an economic downturn, fuel shortages, and political instability, which materially affected ASC functioning [71–73]. This context enabled examination of how channels were disaggregated and reorganised over time to maintain food availability. This section provides an overview of the ASC system in Sri Lanka by discussing the organisation of ASC channels, common spatial ecologies, the nature of the long-term disruption, and government and digital technology-related interventions that emerged to restore food security during the disruption period.

3.3.1. Organisation of Key ASC Channels in Sri Lanka

Sri Lanka has a unique organisation of its ASCs. Figure 3 (adapted from Chandrasiri, et al. [74], Gunarathna and Bandara [75]) depicts the materials and the logistics flows within the ASC system in Sri Lanka, demonstrating the three segments of the ASCs: production, logistics, and consumption.

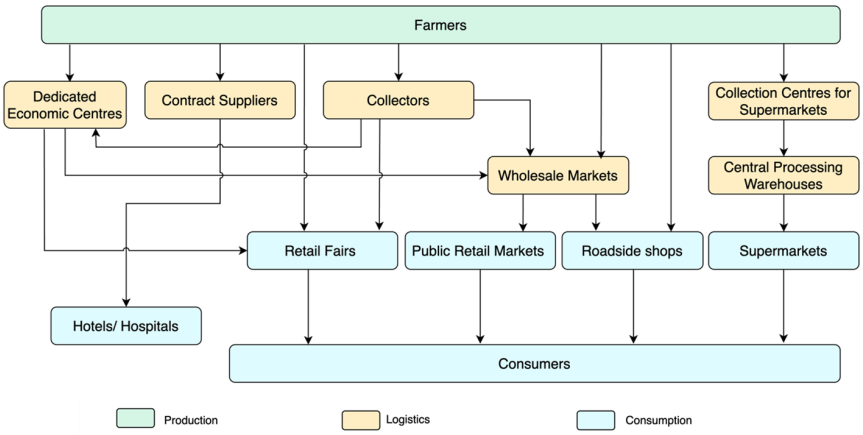


Figure 3. Material and logistics flows of the agri-food supply chain system in Sri Lanka. Adapted: Chandrasiri, Dharmapriya, Kulatunga, Ratnayake, Wasala and Weerakkody [74],Gunarathna and Bandara [75].

- **Production:** Farmers operate across dry/ wet/ intermediate agro-climatic zones and by elevation (up-country vs. low-country), rotating crops with Yala (dry) and Maha (wet) monsoon seasons, ensuring a year-round supply. The system is climate responsive but labour intensive with limited mechanisation.
- **Logistics:** The logistics segment relies on intermediaries, including collectors, wholesalers, distributors, traders, and transporters, who aggregate, store, and redistribute produce across the country. Key nodes in this network include collection centres, government-run Dedicated Economic Centres (DECs), farmers' markets (known as "pola" in the local language), public retail markets, roadside vendors, and supermarket collection hubs. Table 5 outlines the functions of each node.

Table 5. Definitions of ASC distribution nodes.

Entity	Definition/Role
Collection centre	Small-scale facilities near farming areas where farmers drop off produce, often operated by traders, cooperatives, or supermarket chains.
Dedicated Economic Centre (DEC)	Large government-established wholesale markets act as aggregation hubs between producers and urban wholesalers and retailers. E.g., Dambulla DEC
Retail Fairs (Farmers' Market) (*Pola*)	Periodic open-air markets where farmers or small vendors sell directly to consumers. These take place weekly or on specific days. In the local language, it is termed as "*Pola*". These represent a form of short food supply chains, common in both rural and urban areas.
Public retail markets	Permanent, municipal-managed markets in towns and cities where consumers access a wide variety of produce and food items
Roadside shops/ Informal Vendors	Permanent, municipal-managed markets in towns and cities where consumers access a wide variety of produce and food items. Often supplied by wholesalers or intermediaries, not always by farmers.
Supermarkets' collection centres	Large retail chains such as Cargills and Keells operate their own collection centres in production zones to gather and inspect produce before it reaches retail shelves. These centres are equipped with grading, packing, and cold chain facilities. After aggregation, the produce is transported to a central processing unit in Colombo and then distributed to supermarket outlets located primarily in urban areas.

Sources: Chandrasiri, Dharmapriya, Kulatunga, Ratnayake, Wasala and Weerakkody [74],Gunarathna and Bandara [75].

- **Consumption:** Demand is concentrated in the Western Province, particularly in Colombo, which has the country's highest population density and income levels. Yet it produces very little food, relying heavily on inflows from rural regions. This structural imbalance, high demand but minimal production, made Colombo especially vulnerable to severe supply disruptions during COVID-19.

3.3.2. Common Spatial Ecologies

The study applied Sri Lanka's common administrative typology, urban, semi-urban, and rural [76,77], as an analytic lens on sourcing behaviours and channel access. Urban areas represent dense, service-based consumption hubs [78,79]; rural areas are sparsely populated, agriculture-dominant production zones [80,81]; and semi-urban areas fall in between the infrastructure [76,77], with mixed infrastructure, commerce, and small-scale gardening. Given the contextual ambiguities, this study adopted the typology as an analytic lens, operationalised in Table 6, to inform participant selection and comparative analysis based on the criteria important for purchasing food [82] in different spatial ecologies.

Table 6. Classification of spatial ecologies based on where consumers purchase food.

Factors	Urban	Semi-Urban	Rural
Land area	Very small	Small	Large
Household income	High	Medium	Low
Distance to the closest supermarket (around)	<1 km	1–5 km	>5 km
Number of supermarkets within 2 km radius	>5	~1	~0
Number of grocery shops within 2 km radius	10+	5+	1+
Purchase from supermarkets	Very high	Medium	Extremely low
Direct purchasing from farmers	No	Unusual	Available
Home gardening	Low	Medium to high	High
Technology access	High	Medium to high	Low

3.3.3. Long-Term Disruption Timeline and Interventions

From March 2020 to 2022, Sri Lanka experienced two years of nationwide and partial lockdowns due to COVID-19, which were further compounded by overlapping crises. (Four pandemic waves, the fertiliser ban, political instability, the economic downturn, and the fuel shortage collectively produced a prolonged, system-wide disruption of ASCs). Figure 4 illustrates this timeline.

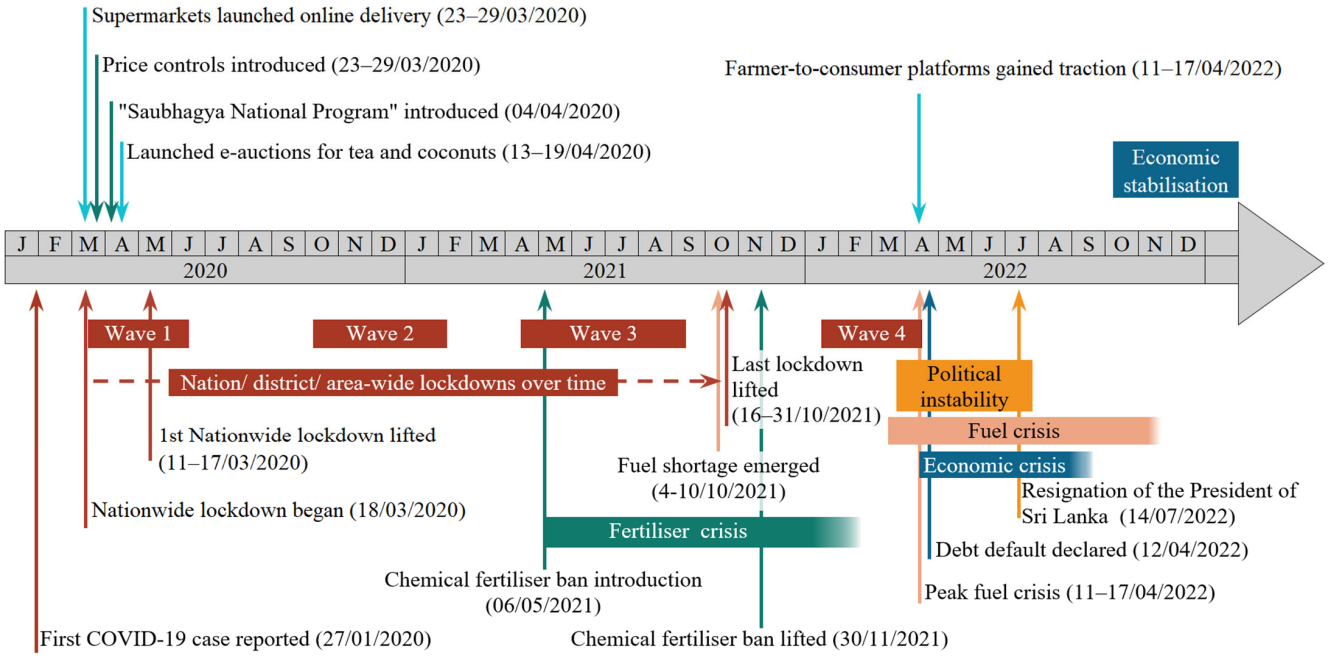


Figure 4. Key events during the total disruption duration.

The impact of COVID-19 affected different parts of the country in different ways. Other disruptions that occurred concurrently or afterwards affected the severity and duration of the disruptive period. However, since March 2020, Sri Lanka has experienced nationwide or partial lockdowns for two years due to the COVID-19 pandemic, which has been further intensified by additional disruptions. Figure 4 provides a rough timeline of how different overlapping disruptive events (four waves of COVID-19, fertiliser ban, political instability, economic crisis, and fuel crisis) occurred over 2020–2022, resulting in a long-term disruption of ASCs.

Technology adoption during the COVID-19 period: Before COVID-19, digital purchasing in Sri Lanka was moderately popular among urban consumers, mostly for non-food items through platforms such as eBay, Kapruka, AliExpress, Takas.lk, MyDeals.lk, WOW.lk, and ikman.lk [83,84]. Agri-food e-commerce remained limited but expanded rapidly during lockdowns [85,86].

Government Policy Interventions: To ensure food security under restricted mobility, the government introduced measures such as maximum retail prices on essentials, import restrictions, and special distribution arrangements, including dedicated trains to transport produce [87,88]. The *Saubhagya* national programme was launched to promote one million home gardens, strengthening household-level food supply [88]. Funds were also allocated for fertiliser imports, although a sudden 2021 ban on chemical fertilisers (intended to shift towards organic methods, not as a response to COVID-19) further disrupted production and was quickly reversed [89].

3.4. Sampling and Participants

Data was collected through semi-structured interviews and focus group discussions (FGDs) with a diverse range of ASC stakeholders across urban, semi-urban, and rural regions in Sri Lanka. The study employed Maximum Variation Purposive Sampling (MVPS) [90] to capture diverse perspectives across spatial ecologies and system levels (micro vs. macro), ensuring a minimum of two to three participants per subgroup, as previously followed in similar studies [30,90]. Thereby, a minimum of three per consumer category and two per other macro categories were selected. Recruitment involved a digital flyer and snowball sampling (by providing a QR link to a Google Sheet), followed by email scheduling and distribution of the Participant Information Sheet. The participants' details are as follows.

The total number of participants included 46 individuals representing six stakeholder categories (Refer to Appendices A.1 and A.2 for details):

- Production: Farmers (5)
- Logistics/Retail: Wholesalers and logistics providers (2), retailers (6)
- Consumption: Consumers (28—representing a minimum of three per group from each spatial ecology [90])
- Enablers: Agri-tech entrepreneurs (3; technological subsystem), agriculture policymakers (2; social/governance subsystem)

Sampling logic: This sample included micro-level actors (consumers, farmers, retailers) essential for understanding region-specific channel adaptations (RQ1, RQ2) and macro-level stakeholders (policymakers, agri-tech entrepreneurs) necessary for identifying high-level systemic enablers (RQ3) (Refer to Figure 5).

Furthermore, the sample was geographically stratified across urban, semi-urban, and rural ecologies to capture context-specific adaptation patterns. This methodical approach ensured data collection continued until interviews and Focus Group Discussions (FGDs) captured sufficient data on the observed adaptations. Qualitative coding proceeded iteratively until no new codes emerged, confirming that the research successfully achieved thematic saturation across all defined research segments.

The robustness of the findings was established through the continuous process of cross-validating consumer-reported data with insights from other stakeholders. Consumers (N = 28) served as the primary stakeholder group to identify initial event-level changes, such as the emergence of new channels and the drivers within the Cost–Availability–Quality (CAQ) framework. This information was then subject to a validation by successive participants. For example, consumer reports detailing the rapid shift to mobile sellers driven by the need for availability were structurally validated by macro-level actors: wholesalers con-

firmed this involved cross-industry collaborations (e.g., unemployed drivers repurposing resources/ vehicles into food transport), which were structurally enabled by government policy interventions (e.g., transport permits). This rigorous triangulation confirmed that the observed behaviours resulted from system-level reconfiguration mechanisms.

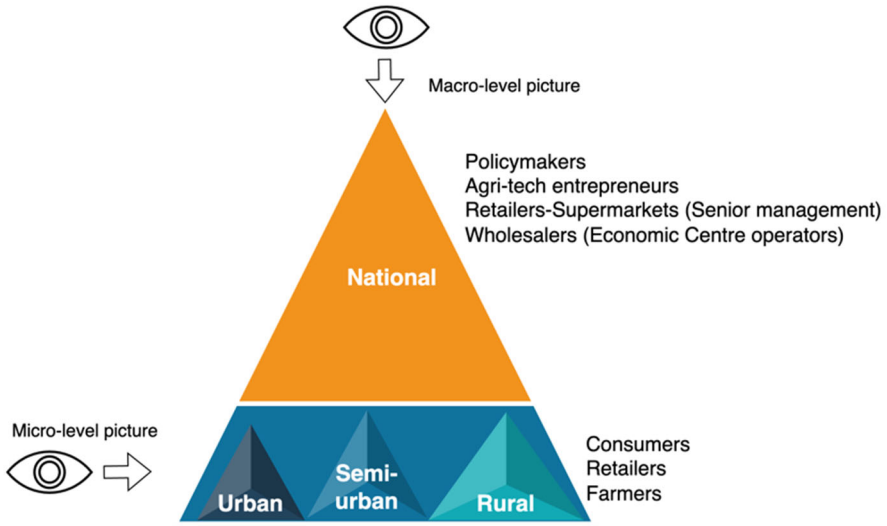


Figure 5. Sample selection based on participants' micro and macro views of the problem.

3.5. Data Collection

All interviews and FGDs were conducted online via Zoom or WhatsApp to ensure accessibility and convenience for participants. Ethical clearance for the study was obtained from the Western Sydney University Ethics Committee (Ethics number: H15555). The data collection involved using semi-structured, open-ended questionnaires tailored for each stakeholder group (consumers, retailers, farmers, policymakers, agri-tech entrepreneurs, logistics service providers), focusing on their experiences and observed changes in ASC processes before, during, and after the pandemic. The primary aim was to capture the adaptations and their evolution over time. The term "channel", referring to the specific pathway of agri-food from producer to consumer, was clearly defined to participants at the outset.

For example, the prompts in the consumer questionnaire included:

1. *Explain the ways that you purchased fresh agri-produce before, during, and after the pandemic. Explain the reasons for selecting each of the channels.*
2. *Have you changed your consumption patterns over time? And how? And why?*
3. *Do you/did you use any technological applications or social media to purchase fresh agri-food? How did it help you overcome the issues?*

The participant interviews and FGDs captured sufficient data on the observed adaptations. To clarify the overall picture during explanations, participants were asked follow-up questions exploring why they shifted to different channels, how the behaviours related to those adaptations evolved over time, and if they used any digital technologies to access food during the disruptive period.

Procedures to capture observed adaptations: Participants were introduced to ASC channels with bilingual background materials (English and Sinhala). Demographic and spatial details were verified through introductory questions. Interviews and focus group discussions (FGDs) used bilingual slides with live reading, and a note-taker recorded responses in Google Sheets. Participants reported their channel use as percentages over time; group averages (in FGDs) were calculated where responses aligned, and individual values were averaged otherwise. In addition, some participants illustrated changes through

Behaviour Over Time (BOT) graphs drawn on an iPad, which were later visually validated with participants.

3.6. Data Analysis

All interviews and FGDs were recorded and analysed using structured content analysis [91,92] as follows:

1. First, open coding was conducted to identify adaptations, decision rationales, and enabling factors across different ASC segments.
2. Second, axial coding was performed to group related codes into broader categories such as channel type, spatial ecology, and enabler.
3. Finally, selective coding was employed to integrate these categories into a coherent account that explains channel formation, transitions, and enablers under disruption.

This study compared channels before, during, and after the COVID-19 pandemic, examining adaptations using Cost–Availability–Quality (CAQ) criteria and spatial ecology. The following analytical tools and frameworks were useful in classifying the data.

This study utilised five tools and frameworks to conduct the content analysis. Out of these five, two existing frameworks/ tools, such as Behaviour Over Time (BOT) graphs and Viability Adaptation Strategies, were utilised in RQ2 and RQ3. During this study, an ASC classification framework was developed in RQ1 and utilised in RQ2. Cost, Availability, and Quality attributes were utilised to develop and validate a comprehensive CAQ framework in RQ2. Ivanov [42]'s four supply chain viability adaptation strategies were utilised and validated for the ASC environment in RQ3 as outlined below.

1. **ASC Channel Classification (M1–M4):** Developed from the literature and observed adaptations to typify emergent channels (Refer RQ1 Analysis).
2. **Cost–Availability–Quality (CAQ) Framework:** This research adapted cost, availability, and quality [8] factors to identify and develop a framework from consumers' perspectives on agri-food during long-term disruptions, explaining channel switching during these disruptions (Refer RQ2 Analysis).
3. **Behaviour-Over-Time (BOT) Graphs:** BOT graphs (reference modes) were used to track the shift in popularity of ASC channels across phases (pre-, during-, and post-disruption). They capture recurring behavioural patterns over time, offering systematic insights for decision-making [93] (Refer RQ2 Analysis).
4. **Viability Adaptation Strategies:** Ivanov [42] proposed four adaptation strategies for the manufacturing and production sector during a long-term disruption situation. Those strategies are intertwined, including scalability, substitution, and repurposing. This research utilised these four strategies and empirically validated them (Refer to RQ3 Analysis).

4. Results and Discussion

This section reports findings from the content analysis, organised to directly answer the study's research questions, RQ1, RQ2 and RQ3.

4.1. RQ1-Emergent ASC Modes

Step 1: Identify conventional and unconventional channels

Based on the empirical study, six emerging unconventional channels were identified as significantly popular and widely utilised during the disruption, regardless of spatial factors. The study examined how consumers accessed food during the COVID-19 disruption and identified several unconventional channels that became prominent when traditional agri-food supply chains faced limitations in accessibility and availability. These emergent modes

were identified from consumer responses and cross-validated with feedback from other stakeholders and are outlined below:

- **Home gardening:** Many consumers, particularly those with access to land and the necessary resources, began cultivating their own food. Home gardening quickly became a direct means of securing food supplies during the disruption.
- **Food Sharing:** Households with surplus produce, particularly home gardeners, engaged in sharing or exchanging food within their communities. This practice created informal safety nets, enabling access to agri-food in the absence of a reliable formal supply.
- **Formal online channels:** Beyond the pre-existing group of e-commerce users, a significant number of consumers shifted to online platforms as their primary source of agri-food. In response to rising demand, several new e-commerce platforms emerged to facilitate food distribution.
- **Informal online channels:** Local farmers and small-scale sellers who could not access established e-commerce platforms, as well as established retailers, turned to informal online methods, such as WhatsApp groups, Facebook groups, other social media channels, and phone calls, to reach consumers.
- **Mobile sellers:** Although mobile vendors had a limited role before the pandemic, their importance grew substantially during this period. With restrictions limiting consumer mobility and regulations eased for vendors, mobile sellers emerged as a widely used supply channel.
- **Roadside selling:** This was a common way of selling fresh food when the traditional markets were closed. Additionally, mobile vendors also sold along the roadside during that time.

To address RQ1, the study identified that the above-mentioned unconventional channels gained popularity during the disruption period, whereas traditional channels such as supermarkets, urban agri-food shops, and farmers' markets (Pola) became less prominent. Furthermore, the analysis validated three fundamental aspects—Availability, Cost, and Quality—of the ASC channel selection proposed in [8], which determine how consumers fulfil their agri-food requirements through either conventional or unconventional channels during a long-term disruptive situation. Most consumer participants further confirmed that **availability** was the most critical factor during the disruption, which explains the increased preference for unconventional channels over traditional ones.

Step 2: Develop M1–M4 ASC Modes

Existing classifications (Refer to Table 1) primarily focus on conventional channels under stable conditions and do not fully represent access in the disruption era. For instance, home gardening (also known as self-growing) and community food sharing emerged as major sources during the COVID-19 pandemic but were not explicitly stated in prior classifications. Hence, there is a need for a generic ASC classification system that captures all adaptations, including those observed during periods of disruption.

In Step 2, this study developed four distinct modes of fresh food supply channels based on the empirically identified conventional and emerging channels (Step 1) and by adopting relevant existing ASC classifications (Table 1). Those modes are M1—prosumer mode (self-growing), M2—community-based sharing, M3—direct farmer–consumer linkages, and M4—retailer/intermediary-based purchasing. M1–M4 are elaborated in Table 7. The initial development of this classification was presented in Vidanagamachchi and Ginige [8].

Table 7. Classification of fresh agri-food sourcing channels—consumer perspective.

Channel Category (Mode)	Representation of the Material Flow *	Type of Transaction	Key Transactions and Channel Examples	Implications of Cost, Availability and Quality
1. Prosumer Mode (M1)	P→C	One-one	Consumers grow fresh agri-produce in home gardens and consume it directly, becoming both producers and consumers	**Cost:** Very low (self-produced); **Availability:** Limited to what can be cultivated; **Quality:** High freshness and trust, but limited diversity
2. Community-based sharing Mode (M2)	P←→C	One-many Many-many Many-one	Individuals or communities grow or source fresh agri-produce and share it within their networks. This includes neighbour-to-neighbour exchanges, urban gardening groups, and organised community or NGO-based food-sharing initiatives.	**Cost:** Often free or very low (donation or exchange basis); **Availability:** Moderate, dependent on surplus and social networks; **Quality:** High, as produce is locally grown and minimally handled;
3. Direct Farmer-Consumer Mode (M3)	P→(M)→C	Many-many	Consumers purchase directly from farmers through local markets, mobile vendors, or digital ordering systems. Farmers may use their own or shared logistics.	**Cost:** Lower than retail due to reduced intermediaries; **Availability:** Moderate, limited by production cycles and location; **Quality:** High, owing to freshness and reduced handling.
4. Supply chains with intermediaries (M4)	P→I_1→I_n→C	Many-many	Consumers buy fresh agri-produce that were grown by distant farmers from supermarkets/shops, where multiple intermediaries are involved in sourcing and supplying the produce to the supermarket, which then serves multiple consumers.	**Cost:** Higher due to intermediary margins and logistics costs; Availability: High, supported by large-scale networks; **Quality:** Variable: Standardised but may compromise freshness due to longer storage and transport.

Note: Cost, availability, and quality are consumers' decision factors for channel switching. Their levels of influence are listed under each factor, and the factors are highlighted in bold. * (P = Producer, M = Market, C = Consumer; I = one or more Intermediaries, n = number of intermediaries).

Step 3: Interpreting Channel Adaptations Through the Iceberg Metaphor

The observed adaptations in Step 1 and M1–M4 classification in Step 2 can further be visually interpreted through the iceberg metaphor (Figure 6), which was adapted from Vidanagamachchi, Ginige and Nakandala [9], where during a long-term disruption, the less visible or unconventional channels beneath the surface become more prominent, while conventional channels above the surface (such as supermarkets and city-based shops) lose prominence due to disruption impacts. Hence, COVID-19 revealed the coexistence of M1–M4 modes of fresh food supply channels, rather than dominance by a single mode.

Among these, M1 (self-growing), M2 (community sharing) and M3 (local or mobile-based direct channels) served as critical stopgaps to ensure food access when M4 (intermediary-based chains) faltered.

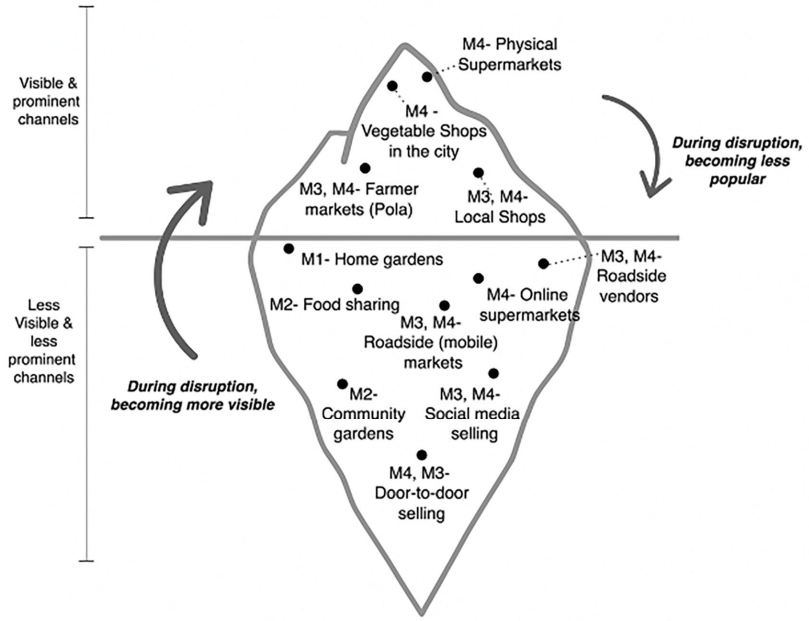


Figure 6. Emergent agri-food supply channels during the COVID-19 pandemic.

4.2. RQ2—Spatial Ecology Patterns, Channel Choice, and Transitions

Step 1: Develop Behaviour Over Time (BOT) graphs

During interviews and FGDs, participants reported their channel use as time-based percentages, averaged across groups or individuals, with selected changes visualised through BOT graphs and validated with participants. Sections 4.2.1–4.2.3 illustrate the developed Behaviour Over Time (BOT) graphs (Figures 7–9), and consumer narratives demonstrate how agri-food sourcing channels (M1–M4) evolved across rural, semi-urban, and urban ecologies before, during, and after the COVID-19 disruption.

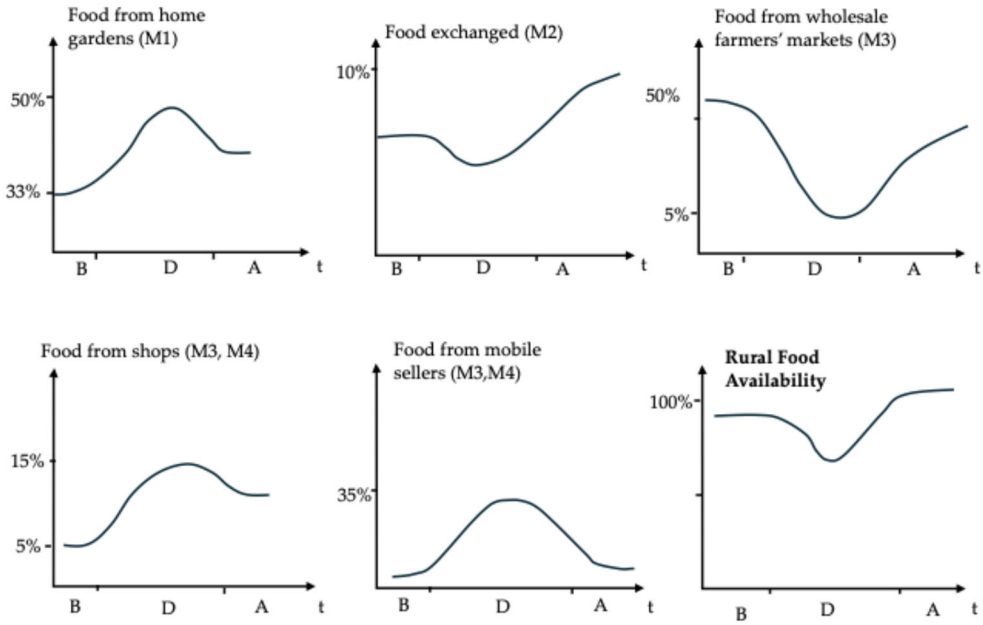


Figure 7. BOTs of rural channels and rural food availability; (B—Before, D—During, A—After).

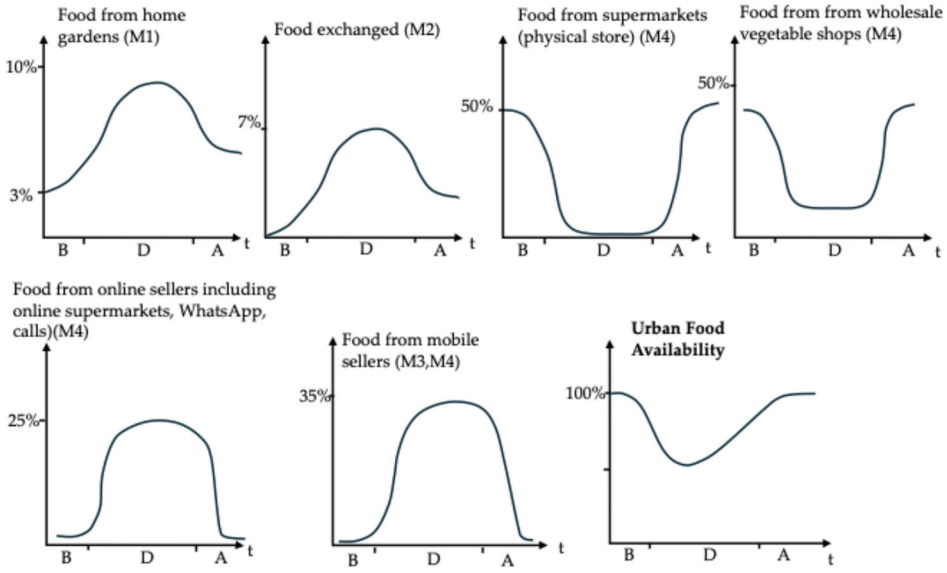


Figure 8. BOTs of the average amounts of food purchased from each urban channel and urban food availability; (B—Before, D—During, A—After).

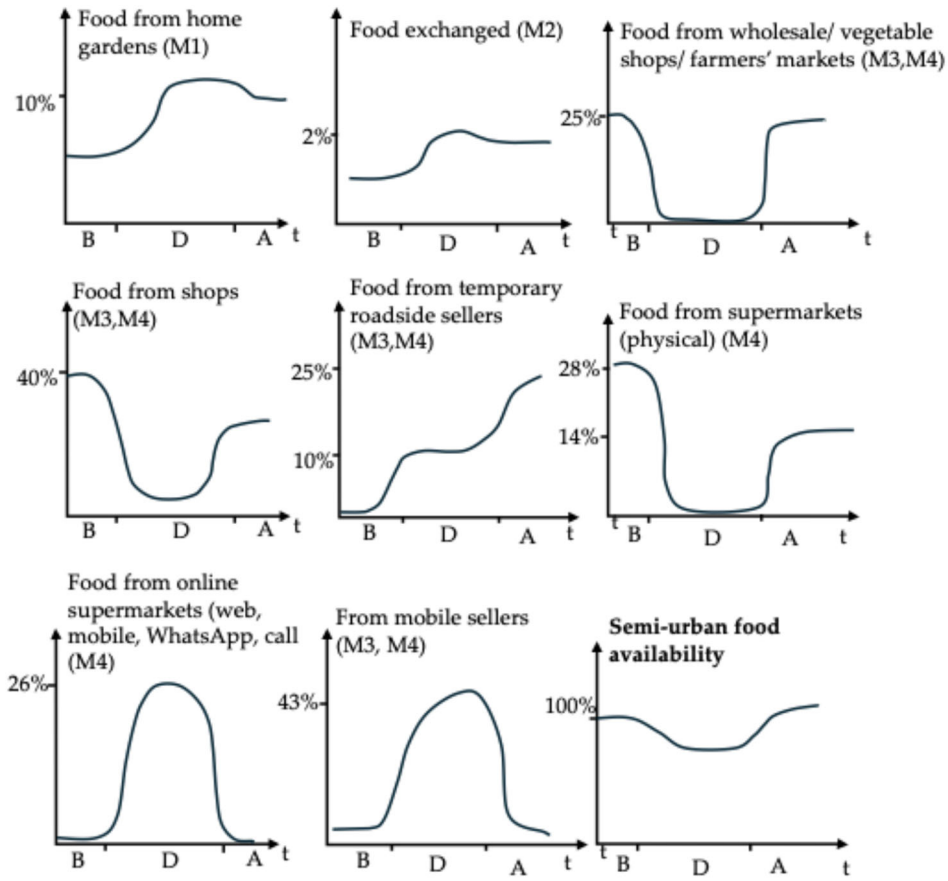


Figure 9. BOTs of the average amounts of food purchased from each semi-urban channel and semi-urban food availability (B—Before, D—During, A—After).

Step 2: Analyse patterns of behaviour

Based on the developed BOT graphs, it can be observed how each spatial ecology (urban, semi-urban, rural) influenced the consumers' choice of and transitions between these channels. Each spatial context displayed a distinct combination of Cost, Availability, and Quality (CAQ) dynamics, reflecting the adaptive mechanisms and trade-offs that

shaped channel transitions during the disruption. Table 8 presents the key empirical findings for RQ2, based on this analysis.

Table 8. Comparison of prominent ASC channels in the three spatial ecologies.

Mode	Urban	Semi-Urban	Rural
M1. Prosumer (Home gardens)	Limited space; small scale; helped reduce Cost; boosted Quality; Availability constrained	Moderate adoption; space allowed more Availability; reduced Cost; good Quality	Core source; met all three (C, Q, A) with high self-sufficiency; scaled up during COVID
M2. Community Sharing	Minimal due to distancing; some social media-based exchanges; mainly Availability support	Stronger reliance; relatives and neighbours provided Cost-free Availability; Quality trusted	Very strong; ensured Availability; reduced Cost; maintained Quality through local trust
M3. Direct Farmer–Consumer (markets, roadside, mobile sellers)	Pre-COVID markets ensured Cost + Quality; during disruption shifted to mobile sellers for Availability	Pre-COVID mix (markets + shops); during COVID mobile sellers ensured Availability, with reasonable Cost/Quality	Farmers' markets disrupted; adapted to mobile/local selling; supported Availability and Cost, variable Quality
M4. Intermediary Chains (supermarkets, shops, online)	Dominant pre-COVID (Cost, Quality); during COVID shifted online/WhatsApp for Availability; post-COVID hybrid with click and collect	Local shops central pre/during/post; provided balance of C, Q, A; supermarkets less trusted post-COVID (fertiliser issues)	Supplementary only; during COVID local shops filled gap for Availability; less important otherwise

Step 3: Develop the CAQ framework

From the evidence gathered through RQ1 and RQ2, as well as the literature, this step justifies the role of CAQ factors in consumers' channel choice, considering them as the intersection of ASC performance and their need for food security.

The following sections address each step:

Step 1: Develop Behaviour Over Time (BOT) graphs

4.2.1. Rural

Channel behaviour: Before the pandemic, rural consumers relied on M1, M2 and M3 (home gardens, food sharing, and farmers' markets) for Cost, Quality, and Availability. During lockdowns, M3 (farmers' markets) declined while M1 and M2 (home gardens and food sharing) expanded, and M3 and M4 (mobile sellers and local shops) filled retail gaps (Figure 7).

Reasons: Strong cultivation capacity and community ties fostered self-sufficiency during disruption. Supported by home gardening programs, households expanded their crop diversity, exchanged produce through trusted networks, and maintained a continuous supply via Wholesale Dedicated Economic Centres (DECs) and local retailers, ensuring stable food availability despite restrictions.

Impact on food availability: An initial dip in food availability was quickly recovered as households stabilised their supply through M1, M2 and M3 modes. The CAQ balance was restored primarily through availability recovery, sustained by low-cost and high-quality homegrown produce.

The above findings demonstrate that rural areas displayed high adaptive capacity due to proximity to production and strong social networks. These systems maintained low Cost, high Quality, and sustained Availability, making rural ecologies the fastest to restore food availability.

4.2.2. Urban

In comparison to rural BOTs, urban BOTs revealed different adaptation patterns (Refer to Figure 8).

Channel behaviour: Before COVID-19, supermarkets (M4) and vegetable markets (M3, M4) dominated urban food sourcing for convenience and quality. Lockdowns disrupted these channels, making supermarkets inaccessible to many. Consumers shifted to digital supermarkets (M4 digital), WhatsApp-based orders, and mobile sellers (M3, M4), while small home gardens (M1) emerged as symbolic adaptations.

Reasons: Urban consumers prioritised availability over cost or quality due to mobility restrictions. The availability of food dropped drastically due to lockdowns, as production occurs in rural areas. Retailers diversified services through phone, WhatsApp, and cash-on-delivery, while households replaced fresh produce with packaged foods for safety, redefining quality around hygiene.

Impact on food availability: Availability recovered through M4 digital and M3 mobile channels, valued for their accessibility and safety, despite the higher cost. After COVID-19, supermarkets adopted hybrid models like click-and-collect, and mobile and online channels remained integral to urban food systems.

Hence, urban recovery was digitally led, where M4 digital intermediation and M3 last-mile mobility became critical lifelines for maintaining availability. During this period, cost and quality considerations were temporarily subordinated to secure access.

4.2.3. Semi-Urban

Channel behaviour: Semi-urban consumers exhibited hybrid behaviour combining urban and rural traits. Before COVID-19, they balanced M3 farmers' markets, M4 local shops, and M1 home gardens for cost and freshness. During the pandemic, M1 home gardening and M2 sharing increased, while M3 mobile sellers and M4 shops became key channels. Some also adopted M4 online supermarket orders for packaged goods.

Reasons: Moderate land availability supported small-scale cultivation, and community trust enabled food exchange. Many consumers checked product availability through mobile or social media before shopping. Local shops and roadside vendors offered proximity and price benefits, while digital tools improved efficiency.

Impact on food availability: Post-pandemic, semi-urban consumers maintained a balanced mix of M1–M4 channels. Reliance on supermarkets declined as consumers preferred trusted local shops and community networks for the assurance of freshness and safety. Over time, quality and trust became stronger determinants than price.

Therefore, semi-urban ecologies institutionalised a mixed model combining proximity, community exchange, and local retail, achieving long-term stability across Cost, Quality, and Availability.

Step 2: Analyse patterns of behaviour

4.2.4. Key Insights on Channel Behaviours

Across the three spatial ecologies, channel transition and CAQ dynamics followed distinct behaviours. The observed adaptations show a spectrum from highly localised, self-sufficient arrangements (M1 and M2) to large-scale, intermediary-heavy structures (M4). During COVID-19, consumers relied on all four modes, with adaptations occurring

based on Availability, Cost, and Quality, highlighting the adaptability and coexistence of different channels in times of disruption, as summarised in Table 8.

- Rural recovery was production and community-driven, maintaining all three CAQ factors through self-sufficiency.
- Urban recovery was digitally driven, focusing on Availability through new intermediation models (M4 digital platforms, M3 mobile sellers).
- Semi-urban recovery emerged as a hybrid, blending self-production, local shops, and selective digital adoption.

Across all contexts, Availability was the dominant driver during the disruption, while Cost and Quality regained importance post-pandemic. These results show that CAQ trade-offs varied contextually, yet all ecologies demonstrated path-dependent recovery trajectories, leading to diversified, resilient, and viable agri-food supply chain configurations.

Step 3: Develop the CAQ framework

4.2.5. Rationale and Validation of Cost–Availability–Quality Framework

Building on earlier work that identified Cost, Availability, and Quality (CAQ) as key criteria influencing consumer channel selection in agri-food systems during long-term disruptions [8], this study clarifies how these dimensions connect consumer food security expectations with agri-food supply chain performance outcomes. Findings from RQ1 and RQ2 confirmed that consumers' channel-switching behaviour across spatial ecologies was primarily driven by Availability, followed by Cost and Quality. The CAQ framework (Figure 10), therefore, rationalises this hierarchy and explains its conceptual basis, further reinforcing the justification for the varied observations of channel use across spatial ecologies.

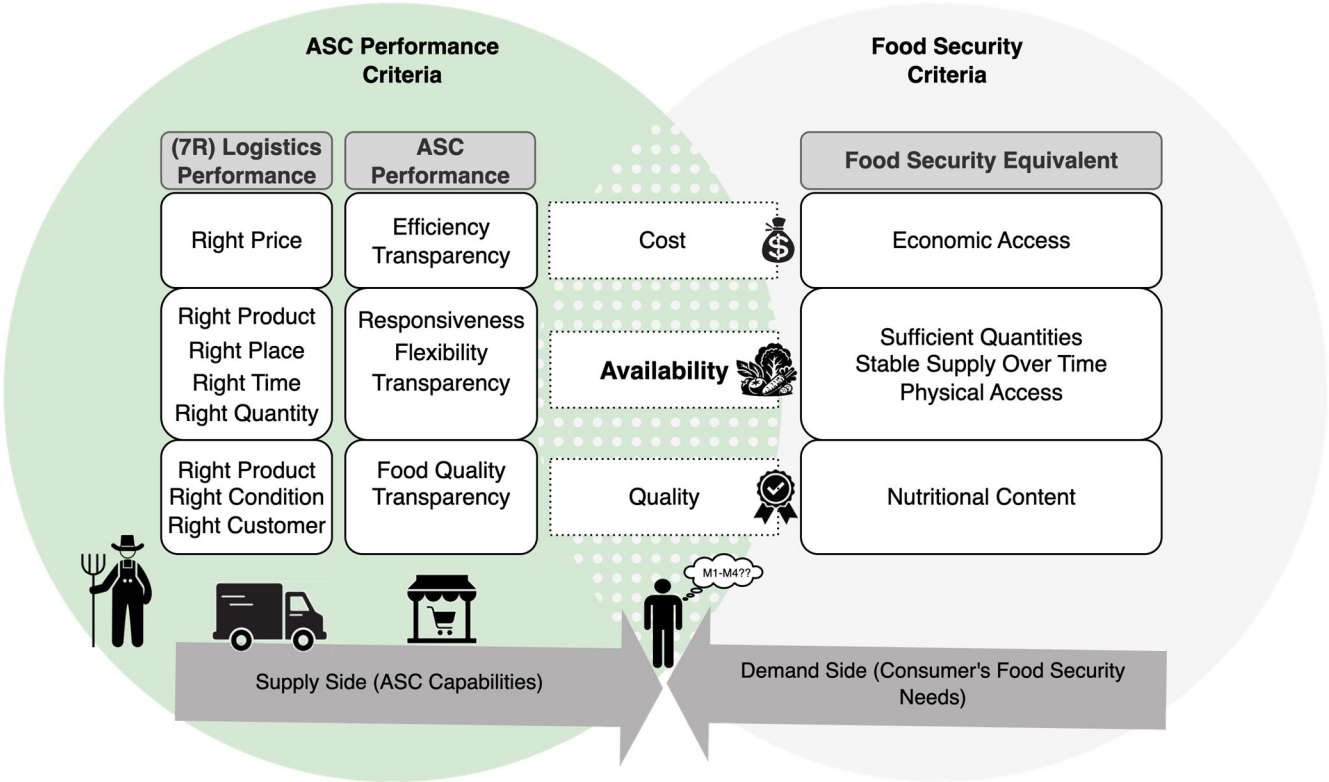


Figure 10. Decision criteria for selecting ASC channels during disruption (CAQ Framework).

The framework bridges the supply side (ASC performance capabilities) and the demand side (food security needs). The supply side represents the individual ASC performance draws on three established frameworks: the 7Rs of logistics management (right product, right place, right time, right quantity, right condition, right price, and right customer) [94–96]; Aramyan, *et al.* [97]'s ASC performance measurement criteria; and Stranieri, *et al.* [98]'s ASC transparency dimension.

While transparency (the availability of accurate information) underpins all three C, A, Q dimensions, their specific relationships with ASC performance criteria are as follows:

- **Cost** is linked to the right price, reflecting production, logistics, and transaction efficiency that minimise supply chain costs.
- **Availability** corresponds to right product, right place, right time, and right quantity, representing responsiveness and flexibility that ensure timely and sufficient supply to meet consumer demand and prevent shortages.
- **Quality** aligns with right product, right condition, and right customer, encompassing product quality (appearance, taste, shelf life) and process quality (traceability, storage, transport, and working conditions), supported by transparency and food safety standards.

Conversely, the demand side represents consumers' food security, focusing only on what aligns with the C, A, and Q parameters, because food security is a multidimensional and broader concept than what ASCs alone can deliver, encompassing social, economic, and policy dimensions [3] beyond supply chain capability. From a food-security perspective, these parameters align with affordability (economic access), consistent physical access, and the availability of safe and nutritious food) [3].

The framework, therefore, emerges from the intersection of C, A, and Q - equivalent food security criteria and ASC performance capabilities, offering a practical lens to interpret consumer channel-switching behaviour during long-term disruptions. It integrates consumer, logistics, and food security perspectives, capturing the key trade-offs that shaped channel transitions during disruption. Among these, Availability emerges as the dominant factor that determines continuity of access, with consumers valuing the assurance of a steady food supply over Cost or Quality when conditions become constrained. As consumers shift between M1–M4 channels, they continually compare the CAQ dimensions, seeking affordable prices (Cost), sufficient and reliable access (Availability), and acceptable freshness and safety (Quality). These comparative evaluations shape channel preferences across spatial ecologies, revealing that while cost and quality remain relevant, availability ultimately dictates which channels are perceived as viable during disruption. Hence, Cost, Availability, and Quality together represent both what ASCs can deliver and what consumers prioritise in securing food under constrained conditions, highlighting how ASCs contribute to (but cannot solely ensure) food security.

Based on the CAQ framework, Table 9 defines Cost, Quality and Availability for consumers under long-term disruptive conditions.

Table 9. Definitions of Cost, Availability, and Quality for consumers under disruptive conditions.

Dimension	Logistics (7Rs)	ASC Performance	Food Security	Consumer Interpretation in Disruptive Times
Cost	Right Price	Efficiency Transparency	Economic access	Affordability of food under constrained budgets, accounting for rising prices, delivery fees, and inflation

Table 9. *Cont.*

Dimension	Logistics (7Rs)	ASC Performance	Food Security	Consumer Interpretation in Disruptive Times
Quality	Right Product Right Condition	Food quality Transparency	Nutritional content	Assurance of safe, fresh, and nutritious food despite reduced variety, compromised handling, or shorter shelf life
Availability	Right Product Right Place Right Time Right Quantity	Responsiveness Flexibility Transparency	Physical access Stable supply over time Sufficient quantities	Reliable access to enough food when and where needed, even under lockdowns, shortages, or transport breakdowns

4.3. RQ3—System-Level Enablers of Channel Adaptation

RQ2 revealed that adaptation patterns varied significantly across spatial ecologies, where similar forms of adaptation occurred but to different extents. Rural areas relied on localised production and community exchange; semi-urban areas demonstrated hybrid characteristics where digital and physical linkages coexisted and evolved; and urban systems adapted primarily through digital platforms and logistics coordination. These spatial variations indicate that adaptation capacity was shaped by context-specific enabling mechanisms. Building on the interview and FGD data, and the findings of RQ1 and RQ2, this section (RQ3) explains who adapted, how they adapted, and what systemic enablers sustained food access across spatial ecologies during COVID-19.

The findings reveal an adaptive reconfiguration of the agri-food supply chain (ASC) ecosystem, consistent with Ivanov [42]'s four viability adaptation strategies, driven by multilevel, cross-industry collaboration, as detailed below.

4.3.1. Systemic Enablers of ASC Adaptations

Based on the findings from RQ1 and RQ2, this study identified that adaptations were primarily driven by three levels of enabling factors, such as macro (policy), meso (technologies, businesses, communities), and micro (consumers, farmers), which were further shaped by spatial characteristics, as outlined below.

- ***Governance and Policy Coordination (Macro-level)***

Government coordination and policy interventions were among the most critical enablers of ASC adaptability. During lockdowns, the continuation of logistics and retail operations was sustained through transport permits, curfew exemptions, and the promotion of home gardening programs. The government encouraged household-level cultivation across all ecologies and facilitated special transport permits that allowed food distribution even under mobility restrictions. These policy actions enabled supermarkets such as Keells and Cargills to maintain food delivery, while rural farmers used government-issued travel passes to transport vegetables and fruits to nearby towns. In parallel, seed-distribution schemes supported household food production. These measures collectively enabled intertwining between sectors and substitution of disrupted channels, forming the regulatory base for system-wide adaptation.

- ***Digital Technologies and Cross-Sector Innovation (Meso-level)***

Digital technologies emerged as a central enabler connecting production, logistics, and consumption. The expansion of online supermarket platforms (e.g., Keells Online, Cargills Online), social media-based ordering (via Facebook and WhatsApp), and delivery apps such as PickMe and Uber Eats provided alternative channels when mobility was restricted.

The partnership between PickMe and Sathosa exemplified intertwining between retail and digital-mobility sectors, while Lassana Flora and Kapruka diversified their e-commerce businesses from gifts to grocery and fresh produce delivery, demonstrating *scalability* and *repurposing*. These innovations bridged the gaps between producers and consumers, particularly in urban and semi-urban areas where digital access was readily available.

Digital technologies supported urban viability by enabling remote transactions and logistics, but their reliance revealed a digital divide. Urban and semi-urban consumers with internet access maintained food access, while those in rural or digitally excluded groups faced inequities. Hence, viability required inclusive solutions, such as phone orders, cash-on-delivery, and simple mobile tools such as WhatsApp, rather than complex e-commerce platforms.

- ***Private Sector, Community, and Social Capital (Meso-level)***

Businesses, NGOs, and community networks jointly acted as intermediaries, maintaining local food access. Private enterprises collaborated with logistics providers and start-ups to distribute food, while small shops and mobile vendors became vital in semi-urban and rural areas. Informal neighbourhood-based sellers and village shops helped restore last-mile access when farmers' markets closed. In semi-urban areas, roadside sellers and junction-based groceries thrived through community trust, whereas in rural areas, households with surplus food shared or sold it through local networks. This community-embedded coordination enabled *intertwining* and *substitution* where formal supply chains were weakened.

- ***Behavioural and Market Adaptations (Micro-level)***

At the micro level, consumers and producers displayed behavioural flexibility that reinforced ASC resilience. Consumers diversified food sources, often shifting from supermarket dependency to informal channels such as mobile sellers, Facebook-based vendors, and neighbourhood markets. They accepted variations in quality and higher costs to ensure availability. Producers and farmers redirected harvests to nearby households or informal traders, while urban consumers increasingly relied on packaged or dry foods due to food safety concerns. These behavioural changes supported *substitution* and *repurposing*, maintaining food continuity across spatial contexts.

- ***Environmental and Spatial–Ecological Conditions (Contextual level):***

As highlighted in RQ2, enabling factors varied across spatial ecologies and ASC modes (M1–M4). In rural areas, where M1 (prosumer) and M2 (community-sharing) modes dominated, established home gardening scaled up to strengthen community food exchange. Fertiliser shortages and transport barriers pushed farmers to adapt cultivation methods and rely on local networks. Households with surplus harvests sold or shared excess produce with shops, mobile vendors, and neighbours, reinforcing M2 to M3 (community to direct farmer–consumer) linkages. In semi-urban areas, overlapping channels of M1, M2, M3 and M4 modes that combine moderate home gardening, supported by available land, with physical proximity to producers and growing digital connectivity. Farmers and intermediaries used Facebook and WhatsApp to market surplus produce to nearby urban consumers, fostering intertwining adaptations between physical and digital networks and supporting scalability. In urban areas, M4 (retail-intermediated) channels, such as Keells, Cargills, and PickMe–Sathosa, prevailed, underpinned by digital logistics and government permits. Overall, enabling mechanisms were context-dependent, influenced by factors such as spatial proximity, infrastructure, digital maturity, and community cohesion.

4.3.2. ASC Viability Through a Multi-Level Enabling System

Collectively, the above findings reveal a multi-level enabling system where policy and governance (macro) provided regulatory flexibility; digital technologies, private enterprises, and communities (meso) ensured connectivity and collaboration; behavioural flexibility (micro) sustained adaptability; and spatial-ecological conditions (contextual) shaped how these mechanisms emerged across rural, semi-urban, and urban systems. Together, these enablers linked production, logistics, and consumption (P–L–C) within diverse ASC modes (M1–M4) and influenced performance outcomes through Cost, Availability, and Quality (C, A, Q) parameters. These enablers served as dynamic capabilities, enabling ASCs to reconfigure resources, form cross-industry linkages, and maintain food access and system viability during prolonged disruptions (Figure 11).

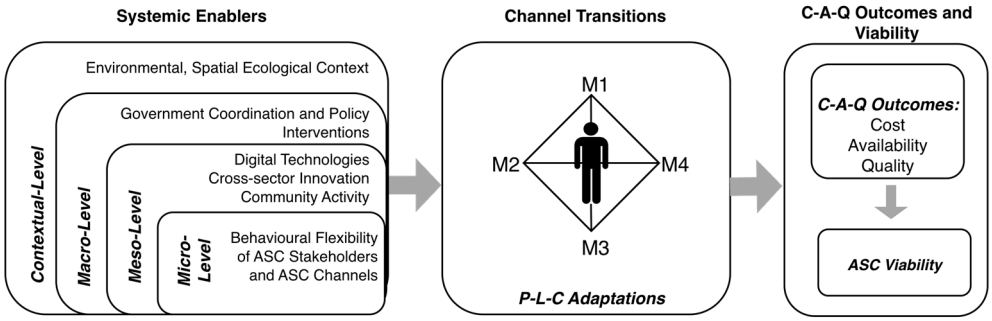


Figure 11. Integrative conceptual model of systemic enablers, adaptive ASC modes, and CAQ-driven ASC viability.

5. Conclusions

This study shows that food security under prolonged disruption requires more than resilience; it requires viability—systemic adaptations that sustain function over time. By analysing how Sri Lanka's agri-food supply chains (ASCs) adapted to COVID-19, the study identifies how food continued to flow from producers to consumers through diverse yet interconnected adjustments across production, logistics, consumption, technology, community, and policy domains.

RQ1 (Emergent structures): A four-mode ASC classification (M1–M4) captured how food reached consumers: self-production (M1), community sharing (M2), direct farmer–consumer exchanges (M3), and retail-intermediated channels (M4). Viability emerged through the recombination and coexistence of these modes rather than reliance on a single channel. During disruption, M1 and M2 activities strengthened as formal retail (M4) weakened, while M3 and M4 channels adapted digitally to sustain access.

RQ2 (Spatial influences): Adaptation patterns differed by spatial ecology.

- Urban systems relied heavily on digitalised intermediaries (M4 online) and mobile sellers (M3) yet faced higher food insecurity due to space constraints and dependence on supermarkets.
- Semi-urban systems adopted hybrid portfolios—expanding home gardening (M1), strengthening sharing (M2), and combining physical and digital linkages (M3 and M4) supported by proximity to producers.
- Rural systems, the most self-sufficient, scaled up M1 and M2 and channelled surplus through M3 local/mobile networks, with M4 playing a minor role.

These variations show that viability was spatially distributed, with strengthened urban–rural linkages facilitating transport and food continuity.

RQ3 (System-level enablers): Adaptations were enabled by policy measures (transport permits, home gardening programmes, market regulations), digital tools (e.g., WhatsApp,

Facebook, PickMe), and community networks (informal redistribution and local exchange). The Cost–Availability–Quality (CAQ) framework clarified consumer channel switching: during crisis peaks, Availability outweighed Cost and Quality; during recovery, Cost and Quality regained influence. This alignment between consumer priorities and ASC performance explains why adaptive practices, such as home gardening and local retail, persisted beyond the crisis.

Implications: Conventional agri-food supply chains cannot remain operational in isolation during long-term disruptions; their continuity depends on systemic interdependence and coordinated adaptation. Therefore, this study provides a case study of how systemic ASC viability was achieved, distinguishing viability from resilience, defining it as the capacity to sustain and evolve under continuous disruption through flexibility, connectivity, and collaboration. Policies that enable adaptive reconfiguration, digital inclusion, and community-based coordination are key to strengthening future ASCs.

Limitations: The study's main limitations stem from its scope, data coverage, and contextual boundaries. It was conducted in a single-country setting in Sri Lanka during the COVID-19 pandemic, followed by compounded disruptions, and relied on a limited sample size drawn from specific geographic regions. These factors may restrict the generalisability of the findings to other geographical or institutional contexts. Furthermore, the analysis focused solely on domestic food systems, excluding the influence of international trade, thereby constraining the model's applicability to globally connected supply chains. Future research should therefore extend the applicability of the ASC viability concept across different regions and incorporate a broader range of long-term disruptions to enhance its robustness and transferability.

Future research directions: Future work should develop system dynamics or agent-based models to simulate ASC viability under varying prolonged disruption scenarios, test the CAQ framework quantitatively, and examine digital–physical integration across various contexts. Cross-country comparisons could further clarify how spatial and institutional factors shape long-term food system viability.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
ASC	Agri-food Supply Chain
BOT	Behaviour Over Time
CAQ	Cost–Availability–Quality
COVID-19	Coronavirus Disease 2019
DEC	Dedicated Economic Centre

FAO	Food and Agriculture Organization (of the United Nations)
FGD	Focus Group Discussion
IoT	Internet of Things
LMICs	Low- and Middle-Income Countries
M1–M4	ASC Four Modes (M1: Prosumer, M2: Community Sharing, M3: Direct Farmer–Consumer, M4: Intermediary-Based Channel)
MVPS	Maximum Variation Purposive Sampling
OECD	Organisation for Economic Co-operation and Development
PDS	Public Distribution System
RQ	Research Question
SCM	Supply Chain Management
SDGs	Sustainable Development Goals
US	United States
VSC	Viable Supply Chain

Appendix A

Appendix A.1. Participant Categories

Table A1. Participant categories.

Stakeholder Group	Type	Number of Participants	Representation	Code *	Geographic Locations and Other Details (U-Urban, SU-Semi-Urban, R-Rural)
Farmers	Interviews	5	Rural areas	F1	1. Ambewela, Nuwara Eliya (Extent: 10 Acre; Crops: Potato, Carrot, Leeks, Cabbage)
				F2	2. Paranagama, Welimada (Crops: Potato, Carrot, Beans, Beet Root, Radish, Rice)
				F3	3. Ampara (Type: Greenhouse farming; Crops: Tomato, Bell pepper, Red Cabbage)
				F4	4. Bandarawela (Type: Polytunnel farming; Crops: Cucumber, Pepper)
				F5	5. Meerigama (Extent: 20 Acre; Crops: Pineapple, Banana, Coconut)
Wholesalers and Logistics service providers	Interviews	2	Rural areas (Economic Centre operators—an *Economic Centre* is a dedicated wholesale marketplace)	W1	1. Meegoda Economic Centre Operator (selling vegetables Wholesale only)—handle distribution as well
				W2	2. Meegoda Economic Centre Operator (Selling vegetables 80% and 20% groceries)
Retailers	Interviews	6	Supermarkets—3 (Urban) (2 with national level experience)	RE_U1	1. U-Moratuwa—Outlet Operations, Manager (Supermarket chain A)
				RE_U2	2. U-Colombo—Island-wide Operations, Senior Manager (Supermarket chain A)
				RE_U3	3. U-Matara, Colombo and Island-wide Operations, Senior Manager (Supermarket chain B)
			Farmers' market—1 (Rural)	RE_R4	4. R-Meerigama local farmers' market
			Vegetable shops—2 (Semi-urban)	$RE_{SU}5$	5. SU-Walgama (small scale shop)
				$RE_{SU}6$	6. SU-Walgama (large scale shop)

Table A1. *Cont.*

Stakeholder Group	Type	Number of Participants	Representation	Code *	Geographic Locations and Other Details (U-Urban, SU-Semi-Urban, R-Rural)
Consumers	Interviews	10	Urban—4 (1 with national level experience)	C_U1	1. Colombo, Western Province
				C_U2	2. Kiribathgoda, Western Province (has experience with working with farmers across the country)
				C_U3	3. Dalugama, Kelaniya, Western Province
				C_U4	4. Colombo 10, Western Province
			Rural—3	C_R1	5. Galkanda, Ampara District, Eastern Province (Farming family)
				C_R2	6. Kurunegala District, North-western Province
				C_R3	7. Udalamatta, Galle District, Southern Province
			Semi-urban—3	$C_{SU}1$	8. Galle District, Southern Province
				$C_{SU}2$	9. Matara District, Southern Province
				$C_{SU}3$	10. Panadura, Western Province
	FGD	18	Urban—2 FDGs, 3 consumers each	C_UFGD1	1. Colombo-6, Western Province 2. Colombo-10, Western Province 3. Colombo-5, Western Province
				C_UFGD2	4. Gampola, Central Province 5. Gelioya, Central Province 6. Mawanella, Sabaragamuwa Province
			Rural—2 FDGs, 3 consumers each	C_RFGD1	7. Ampara- Kethsirigama (Farming family and sell via a Facebook page) 8. Ampara- Jayewardenepura (Farming family) 9. Ampara-Uhana (Farming family); Eastern Province
				C_RFGD2	10. Bandarawela (Farming family), Uva Province 11. Bandarawela (Farming family), Uva Province 12. Buttala, Uva Province
			Semi-urban—2 FDGs, 3 consumers each	C_{SU}FGD1	13. Badulla, Uva Province 14. Ja-ela, Western Province 15. Piliyandala, Western Province
				C_{SU}FGD2	16. Matara, Southern Province 17. Kamburugamuwa, Southern Province 18. Bandaragama, Western Province

Table A1. *Cont.*

Stakeholder Group	Type	Number of Participants	Representation	Code *	Geographic Locations and Other Details (U-Urban, SU-Semi-Urban, R-Rural)
Agri-tech entrepreneurs	Interviews	3	E-commerce—2	ATE 1 ATE2	1. A tech entrepreneur, formerly in the ride-share industry, who has launched a new web- and social media-based business. 2. The CEO of a finance company in the farmer micro-financing sector, testing a proof-of-concept web-based business model.
			Home gardening Mobile app—1	ATE3	3. An academic who also leads a project developing a mobile app that provides knowledge and guidance to home gardeners.
Agriculture policymakers	Interviews	2	National level	PM1 PM2	1. A food security policymaker at the Ministry of Agriculture, who also holds an academic role. 2. The Project Coordinator for the Agriculture Modernisation Project at the Ministry of Agriculture.
Total		46			

* This participant code is used to identify the participant's location within the map of Sri Lanka in Appendix A.2.

Appendix A.2. Spatial Distribution of the Participants Within the Map of Sri Lanka

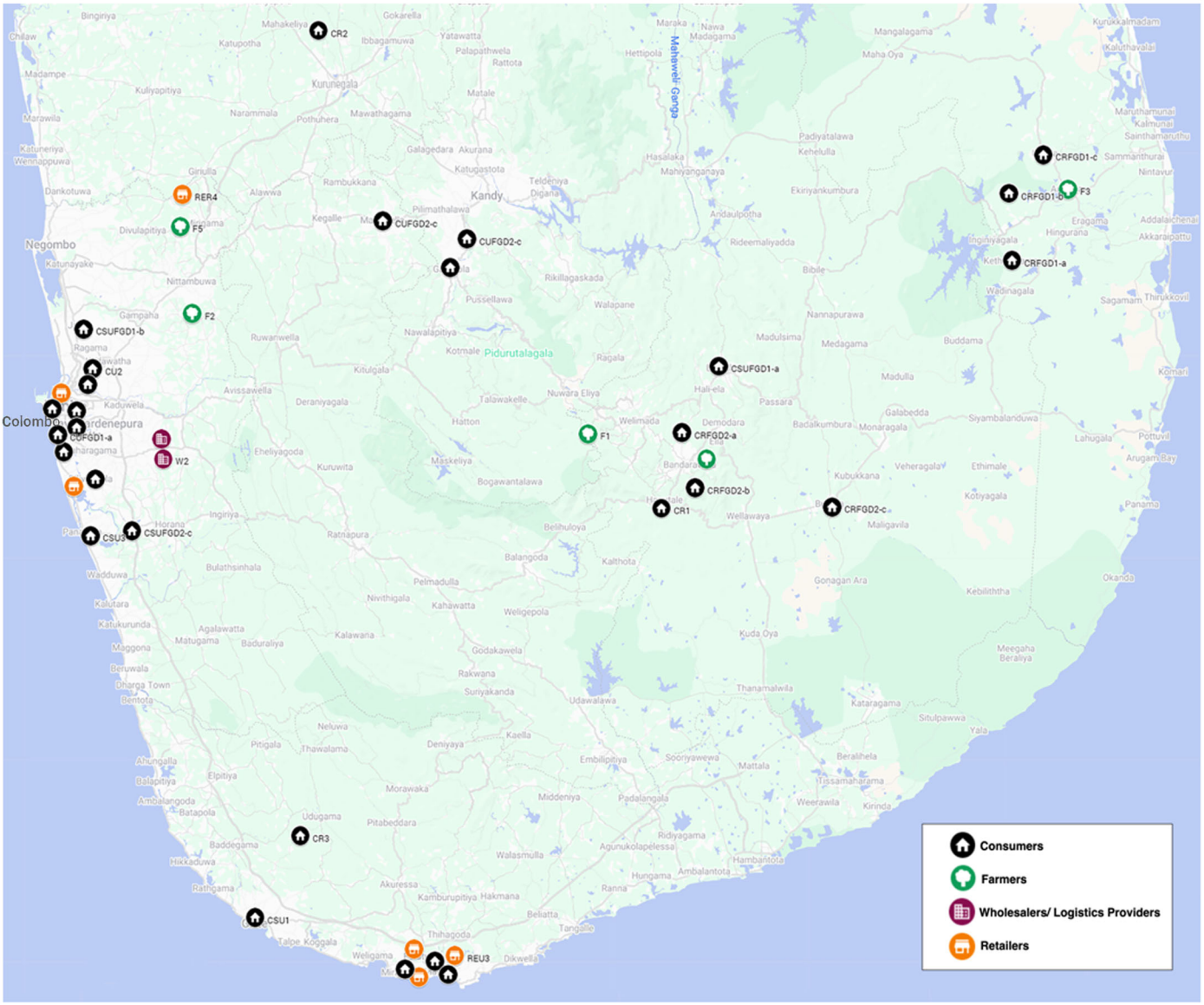


Figure A1. Spatial distribution of the participants within the map of Sri Lanka.

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