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Configuring lean supply chain performance in Indian millet distribution: A fuzzy-set qualitative comparative analysis approach

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Background: The Indian millet sector remains fragmented and inefficient, constraining effective supply chain performance. With growing recognition of millets' role in food security and rural livelihoods, enhancing operational efficiency through lean practices has become crucial.

Objectives: This study identifies and analyses the combinations of conditions that lead to high and low lean supply chain performance (LSCP) in millet distribution across India, addressing key operational challenges in agri-food supply chains.

Method: Using fuzzy-set qualitative comparative analysis (fsQCA), the study evaluates six core conditions: technology integration, farmer coordination, market linkage (ML), inventory control, waste reduction (WR), and standardised processes. Primary data were collected from 132 respondents through structured surveys and field-level expert inputs, and configurations leading to both high and low LSCP were examined based on raw and unique coverage and consistency values.

Results: The analysis reveals multiple sufficient pathways for achieving high LSCP, particularly configurations that combine ML, inventory control, and WR. Technology integration is a sufficient but not a necessary condition, suggesting its effectiveness is context specific. Conversely, the absence of ML, WR, and inventory control consistently contributes to low LSCP.

Conclusion: The fsQCA provides a systematic approach to understanding the configurational dynamics influencing supply chain performance in millet distribution. Operational practices such as ML, inventory control, and WR exert greater influence than standardisation or technology in isolation.

Contribution: The findings offer practical insights for policymakers and supply chain actors, highlighting the need for integrated strategies that strengthen market access, storage infrastructure, and post-harvest efficiency.

Keywords: *fs*QCA; millet; lean supply chain; India; resource efficiency.

Introduction

Over the past few decades, supply chain strategies have shifted from cost-centric models to lean and agile systems, particularly in sectors that demand both responsiveness and resource efficiency (Núñez-Merino et al. 2020; Pertanian et al. 2025). This evolution reflects a broader focus on supply chains that go beyond cost minimisation to also adapt swiftly to fluctuations in demand and supply. As defined by Ghiani, Laporte and Musmanno (2004), 'supply chain management (SCM) encompasses procurement, operations, logistics, and marketing channels through which raw materials are transformed into finished products and delivered to end customers'. Within this framework, the millet supply chain in India continues to face critical challenges, including fragmentation, irregular grain availability and high post-harvest losses resulting from inadequate storage and processing infrastructure (Konde 2024). Small processors struggle with high costs as retailers demand substantial margins, while the short shelf-life of millet flour forces companies to target premium markets, making millet products unaffordable for low-income consumers despite their nutritional benefits (Chandra et al. 2024; Davis et al. 2019). In addition, government

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procurement remains minimal (1% – 15% across millet types vs. 45% – 70% for rice and wheat), depressing farmgate prices and undermining farmer incentives (Chandra et al. 2024). Nevertheless, prospects are strengthening through coordinated national initiatives such as the International Year of Millets 2023 and India's positioning as a global production hub accounting for 80% of Asia's and 20% of global output (Deshpande 2024).

The motivation for this study stems from the growing recognition of millets in India as climate-resilient and nutrient-dense crops with the potential to strengthen food security, promote sustainable agricultural practices and enhance the livelihoods of smallholder farmers (Satyavathi et al. 2021). Despite various policy efforts and promotional initiatives, the millet distribution system in India remains unorganised, with limited coordination among stakeholders, fragmented value chains and inadequate post-harvest management (Konde 2024). A key barrier is the lack of awareness among supply chain actors, especially producers, including the farmers and millet processing industries, regarding the role of integrated supply chain performance in realising profitability. Many producers operate in isolation, focusing narrowly on cultivation and direct selling without recognising that value realisation depends on the efficiency, transparency and responsiveness of the entire distribution system. These inefficiencies are compounded by weak infrastructure, limited resource access and inadequate alignment with market demand.

Against this backdrop, the study addresses the following research questions: (1) *What specific combinations of lean supply chain practices lead to high performance in millet distribution systems?* and (2) *How do these combinations differ across low-resource agri-food contexts where technology, coordination and infrastructure are unevenly distributed?*

By applying fuzzy-set qualitative comparative analysis (fsQCA), the study advances understanding of lean supply chains in smallholder-driven agriculture. Rather than assuming that a single best practice drives outcomes, it will demonstrate equifinality, multiple alternative pathways to high performance and causal asymmetry, where the role of a condition varies across configurations. This shifts the focus from universal prescriptions to context-sensitive bundles of practices, offering a novel theoretical insight for lean supply chain research and practical guidance for strengthening the agri-food supply chain. Therefore, the prime objective of the study is to explore the factors influencing lean supply chain performance (LSCP) in the millet distribution sector. Then, fsQCA method has been utilised to determine the specific combinations of various conditions necessary and/or sufficient for achieving high/low levels of lean performance.

Theoretical underpinning

This study integrates lean supply chain management (LSCM) theory with the configurational approach to causal complexity (Ragin 2009; Schneider & Wagemann 2009) to analyse agri-food supply chains in the Indian context. While lean practices in supply chain emphasise waste reduction (WR), flow optimisation and demand responsiveness (Shah & Ward 2003), its application in millet distribution sector in India, which is attributed to high variability, perishability, infrastructure constraints and institutional fragmentation (Chistnikova, Ermachenko & Gunter 2021; Kazancoglu et al. 2021), necessitates recognition of non-linear interdependencies and contextual contingencies that conventional LSCM models inadequately address.

Review of literature

A supply chain includes the entire flow and transformation of products and information from raw materials to end users, including upstream and downstream activities (Ballou 2009). Effective SCM is a critical factor influencing organisational performance through lower inventory levels, improved process efficiency, higher quality, reduced operational costs and enhanced customer satisfaction (Ugochukwu, Engström & Langstrand 2012). Lean philosophy in supply chain has emerged as a key strategy being globally adopted to stay competitive (Womack, Jones & Roos 2007). The primary focus of LSCM is on cost reduction through eliminating non-value-added (NVA) activities in the supply chain and using a lean strategy to structure these operations to enhance sustainability. According to Shah and Ward (2003), the spirit of a lean supply chain lies in 'delivering products in alignment with customer demand with minimal waste'. According to Ziegler and Stoeger (2008), LSCM is a 'collaborative effort among interconnected organisations that manage the flow of products, services, information, and finances to minimise waste and cost while responding effectively to customer needs'.

The performance of the LSCM must align with broader organisational goals and competitive strategies. Performance measurement quantifies the efficiency and effectiveness of actions taken, which refers to meeting customer expectations, and efficiency relates to the optimal use of resources (Nimeh, Abdallah & Sweis 2018). While measuring the performance of the supply chain, Díaz, Gil and MacHuca (2005) emphasised the integration of financial data along with non-financial indicators such as quality, delivery and flexibility. In the context of millet distribution, measuring lean supply chain practices requires considering the unique challenges associated with agricultural products, such as seasonality, perishability, fragmented stakeholders and limited digital integration (Kheya et al. 2023). The lean millet supply chain performance measure lacks quantitative financial data in Indian agri-product distribution, as it is a very unorganised and decentralised (Roy et al. 2023). Thus, the study relies on qualitative performance indicators that capture flexibility, responsiveness, process efficiency and coordination effectiveness (Díaz et al. 2005; Shepherd & Günter 2011).

In the era of Industry 4.0, the use of technology is considered a powerful enabler of LSCM by enhancing coordination, transparency and efficiency across supply chain activities

(Carrijo et al. 2024; Pertanian et al. 2025). The agricultural sector in India is largely unorganised, and it is marked by fragmented landholdings, weak infrastructure and limited digital literacy, which hinder the widespread adoption of advanced technologies. In Indian agriculture, Pandey and Bolia (2023) emphasised that integrated technological frameworks are essential to improve the value chain, enabling better decision-making and responsiveness to socio-economic and environmental goals. Technologies such as Internet of Things (IoT), artificial intelligence (AI) and blockchain have the potential to transform and streamline traditional agri-food businesses based on data-driven operations (Vernier et al. 2021). Yet, such advanced models that blend digital platforms require physical touchpoints and community partnerships to overcome last-mile adoption hurdles. Similarly, according to Cricelli, Mauriello and Strazzullo (2024), technological clustering and highly customised supply chain configurations can boost agility and resilience. For long-term success, tech adoption must be embedded in supportive ecosystems through farmer collectivisation, phased subsidies and context-sensitive design. Nonetheless, integrating such technologies remains central to transforming millet distribution in India into a lean, efficient and scalable system.

Farmer coordination is crucial in achieving success in LSCM for agri-based products by enabling synchronised production, reducing losses and improving responsiveness to market demands (Banu et al. 2022; Parasuraman et al. 2023). Research shows that farmer-producer organisations (FPOs) improve smallholder bargaining power and ensure consistent grain quality via collective training and resource sharing (Konde 2024). In Odisha and Karnataka, FPO-led aggregation centres reduced procurement costs by 15% by minimising intermediaries (Kumar, Das & Jat 2023). Cuer, Scalco and Satolo (2025) and Chairany, Hidayatno and Suzianti (2022) demonstrated how lean tools such as value stream mapping (VSM) and risk-lean matrices, when used in coordination with farmers, identify inefficiencies and reduce waste in agricultural production, contributing directly to the performance of the LSCM. Roop et al. (2022) further illustrated that small farm holders' adaptive capacity can be significantly enhanced through strategic coordination, allowing better market access and lower post-harvest losses.

Establishing a sustained market network plays a significant role in enhancing the effectiveness of LSCM (Bai, Gao & Lv 2021; Nimeh et al. 2018). The millet market in India is witnessing rapid expansion, with its size projected to grow at a compound annual growth rate (CAGR) of 15.9% between 2023 and 2029, reflecting strong urban demand for packaged and processed millet-based products (6Wresearch 2024). Globally, the millet market is expected to increase from USD 15.3 billion in 2024 to USD 23.4 billion by 2034, at a CAGR of 4.4%, with India emerging as a key contributor to this growth (Pulidindi 2025). Direct-to-consumer (DTC) e-commerce platforms are further reshaping millet trade dynamics by bypassing traditional retail intermediaries, enhancing affordability for consumers, and improving price realisation for farmers (Konde 2024). Bai et al. (2021) claimed that market understanding and marketing alignment with supply operations are essential for effective demand chain management. Similarly, Iyer, Srivastava and Srinivasan (2019) added that market linkage (ML) is a function of learning orientation and partnerships, which build lean capabilities through knowledge sharing and coordinated planning. Thus, emphasising that strong customer relationships and timely information flow are key lean practices that directly impact supply chain and market performance (Nimeh et al. 2018).

Few studies have highlighted the issue of waste and loss in agricultural produce across various operational stages and distribution channels, indicating the necessity of an effective LSCM model (Adenso-Díaz, Lozano & Palacio 2017; Lemaire & Limbourg 2019). Prior studies have pinpointed five key operational challenges, such as demand forecasting, production planning, transportation, inventory control and inefficient harvesting, that contribute to these inefficiencies, with many focused on the cause-and-effect models to understand their interrelations (Anand & Barua 2022; Spang et al. 2019). The functional areas of production, harvesting, distribution and inventory continue to dominate discussions on supply chain optimisation (Paam et al. 2019). Inventory, in particular, demands strategic attention, accounting for nearly half of the capital investment in many agricultural businesses (Anand & Barua 2022). Chistnikova et al. (2021) demonstrated how inventory management at every logistics stage, from raw material to finished goods, can reduce product loss and increase operational effectiveness in crop production chains. However, achieving such efficiency in agriculture is particularly challenging because of the perishability of produce, environmental constraints and the high costs associated with storage infrastructure (Paam et al. 2019).

These challenges are especially evident in the millet supply chain, where multiple points of waste occur during post-harvest handling, storage, processing and distribution. Farmers in India often lack access to proper drying facilities, leading to moisture-related spoilage. Poor packaging, rough handling and the lack of cold storage are key reasons for post-harvest losses. Although millets are more resilient than many other perishables, they remain highly vulnerable to deterioration when exposed to excess moisture and substandard storage practices (Chairany et al. 2022; Elbarky, Elbary & El Haddad 2025; Perdana et al. 2019). Inadequate storage infrastructure, such as the absence of hermetic silos or controlled environments, results in grain loss because of pests, mould and humidity. Spillage, improper grading and contamination further reduce the output during transportation and processing.

Fragmented MLs and unpredictable demand often lead to overstocking or underutilisation of produce, thereby increasing wastage. Lean tools such as VSM (Vostriakova et al. 2021) and training-based waste prevention frameworks (Kharola et al. 2022) have proven effective in reducing inefficiencies and supporting a continuous, cost-efficient flow of agricultural goods. In the Indian context, these challenges can be addressed through the establishment of decentralised drying and storage facilities, the use of affordable moisture-control packaging, enhanced farmer training on post-harvest practices and the integration of technology-driven inventory and demand forecasting systems. In millet chains, cooperative-led coordination can reduce procurement losses by 15% through standardised handling and pooled resources (Perdana et al. 2023). Farmer-producer organisations can be key players in managing logistics, storage and quality control. At the same time, policy support for cold chain infrastructure can minimise inefficiencies across the supply chain.

Similarly, standardisation of the supply chain processes is essential for enriching LSCM by ensuring consistency in production quality, improving coordination among supply chain members (Saeed, Malhotra & Abdinnour 2024) and minimising inefficiencies (Anand & Barua 2022; Elbarky et al. 2025; Perdana et al. 2023; Spang et al. 2019). Standardisation can be achieved through various methods, from simple manual practices to advanced tech-enabled systems. For instance, a study done by Elbarky et al. (2025) in Egypt specified that poor handling and improper transport arrangements in agri-food supply chains can be mitigated through clear work instructions and training. As such, Perdana et al. (2019) noted that manual, non-standardised tasks in rice processing, leading to time and cost inefficiencies, can be better managed through technology and skill development. Lean tools such as VSM, as highlighted by Vostriakova et al. (2021), have proven effective in identifying waste-prone stages and optimising workflows through standardisation. Chairany et al. (2022) developed a risk–lean matrix showing that many causes of food loss in the cayenne pepper supply chain were linked to unstandardised activities. Similarly, Kharola et al. (2022) emphasised that training and skill-building, key enablers of standardised processes (STPs), were among the most critical strategies for WR in the food supply chains. The literature supports that STPs are central to achieving lean performance by minimising waste and enhancing efficiency.

Although existing studies have explored various aspects of LSCM in agriculture, there remains a limited focus on the specific role of STPs in improving supply chain performance, particularly for millets. Most prior research has concentrated on broader lean tools, logistics issues and food loss across general agri-food systems. While some studies mention training and process alignment as partial solutions, the question is whether only standardisation of operational steps is sufficient for lean outcomes. Furthermore, there is a lack of empirical evidence from millet-based supply chains, which face unique challenges because of their decentralised nature and limited technological integration. This study contributes originality by applying a configurational approach (fsQCA) to examine LSCP in the millet sector – an area where prior research has focused mainly on manufacturing supply chains or large-scale crops using regression-based models. By analysing how combinations of factors such as technology use, farmer coordination, ML, inventory control and WR jointly shape outcomes, the study provides a nuanced understanding of pathways to high performance in smallholder-dominated agri-food systems. This study addresses a gap in understanding how standardised procedures can be systematically implemented to reduce waste, improve coordination and ensure consistency in millet supply chains under lean principles. Based on the foregoing discussions, we present the following proposition 1: High supply chain performance in millet distribution emerges through equifinal configurations of lean practices, where different combinations of technology use, farmer coordination, inventory control, waste reduction, market linkage and standardised processes can each generate the outcome. No single practice is universally sufficient, and the effect of any one practice depends on the presence or absence of others, reflecting the causal asymmetry and configurational nature of lean supply chain performance.

Research method and design

Sample and data

The study employed purposive sampling to target respondents directly engaged in managing or facilitating the millet supply chain. Of the 185 individuals contacted, 147 agreed to participate, and 132 complete responses were retained after excluding 15 incomplete cases, yielding a usable response rate of 71.3%, which is considered appropriate for *fs*QCA (Ragin 2009). Data collection was conducted through mixed modes, comprising 58 in-person field surveys and 74 online Google Forms, supplemented by follow-up calls to ensure accuracy. To minimise bias, respondents were drawn from diverse roles including FPOs, processors, distributors, non-governmental organisations (NGOs) and government officials (see Table 2) with at least 6 months of relevant experience.

Although purposive sampling limits statistical generalisability, fsQCA prioritises configurational diversity over random representation; hence, the coverage values in this study reflect context-specific patterns in southern Indian millet supply chains rather than universal probabilities. Table 1 presents the measurement of variables along with their descriptive and reliability statistics. Responses were collected using a 5-point Likert scale. We also acknowledge the potential risk of common-method bias (CMB) and social desirability bias, given that the data are cross-sectional and self-reported. To address this, Harman’s not single-factor test was conducted during exploratory factor analysis, which confirmed that no single factor accounted for the majority variance, suggesting that CMB does not substantially affect the results.

The fuzzy-set qualitative comparative analysis model and calibration

The fsQCA method offers a unique ability to examine causal complexity, which is especially relevant in lean supply chain practices. Unlike traditional statistical methods that isolate the net effect of individual variables, fsQCA allows

TABLE 1: Measurement of constructs.

Variables	Component matrix	μ	σ	CR	α	AVE
LSCP (Arif-Uz-Zaman & Ahsan 2014; Shepherd & Günter 2011)	-	3.19	0.75	0.86	0.91	0.78
Our millet supply chain ensures timely delivery to buyers	0.803	-	-	-	-	-
We can avoid overstocking or wastage of millet during storage and distribution	0.802	-	-	-	-	-
We experience minimal delays or disruptions in our supply chain	0.791	-	-	-	-	-
We fulfil market demand efficiently without keeping excess inventory	0.789	-	-	-	-	-
Our distribution process ensures minimal spoilage or damage	0.727	-	-	-	-	-
We coordinate with suppliers and buyers regularly	0.702	-	-	-	-	-
TEC (Ganbold, Matsui & Rotaru 2021)	-	3.40	1.04	0.92	0.95	0.83
We use mobile phones to access real-time market information	0.728	-	-	-	-	-
We receive agricultural or market-related information through mobile apps, SMS or WhatsApp	0.715	-	-	-	-	-
We use moisture metres and other tools	0.710	-	-	-	-	-
We use online platforms to find buyers	0.690	-	-	-	-	-
We use UPI and online bank transfers	0.611	-	-	-	-	-
FC (Diwakar, Roberts & Quach 2023)	-	3.61	0.88	0.88	0.90	0.74
We have direct contracts with millet farmers	0.661	-	-	-	-	-
We provide regular updates to farmers	0.660	-	-	-	-	-
We coordinate harvest and supply schedules with producers	0.655	-	-	-	-	-
We resolve farmer issues collaboratively and promptly	0.637	-	-	-	-	-
ML (Bai et al. 2021)	-	3.61	0.98	0.91	0.88	0.78
We have access to institutional buyers	0.754	-	-	-	-	-
We receive timely price signals from the market	0.732	-	-	-	-	-
We engage in demand forecasting before procurement decisions	0.710	-	-	-	-	-
We customise our millet products for specific market needs	0.688	-	-	-	-	-
INV (Khalid & Ndolo 2024)	-	3.54	0.97	0.86	0.93	0.71
We maintain only essential inventory to meet current demand	0.832	-	-	-	-	-
We regularly monitor and adjust stock levels to avoid surplus	0.816	-	-	-	-	-
Inventory holding costs are minimised through efficient planning	0.813	-	-	-	-	-
Our millet storage practices are optimised for shelf-life	0.732	-	-	-	-	-
WR (Nimeh et al. 2018)	-	3.29	1.15	0.85	0.94	0.72
We minimise post-harvest losses during handling and storage	0.730	-	-	-	-	-
Packaging and transport processes are optimised to reduce wastage	0.707	-	-	-	-	-
We monitor and report waste levels in the supply chain	0.677	-	-	-	-	-
STP (Saeed et al. 2024)	-	3.50	1.01	0.84	0.89	0.81
We follow standardised procedures for procurement and storage	0.717	-	-	-	-	-
Our production or processing units follow uniform quality guidelines	0.705	-	-	-	-	-
We document and regularly update our operational procedures	0.702	-	-	-	-	-
Employees or partners are trained to follow standard protocols	0.685	-	-	-	-	-

Note: Please see the full reference list of the article, Maharana, N., Chaudhury, S.K., Panigrahi, A.K., Uprety, M., Parida, B., Sarda, V. et al., 2025, 'Configuring lean supply chain performance in Indian millet distribution: A fuzzy-set qualitative comparative analysis approach', *Journal of Transport and Supply Chain Management* 19(0), a1210. https://doi.org/10.4102/jtscm.v19i0.1210, for more information.

LSCP, lean supply chain performance; TEC, tech-integration; FC, farmer coordination; ML, market linkage; INV, inventory control; WR, waste reduction; STP, standardised processes; μ, mean; σ, standard deviation; α, cronbach's alpha for construct reliability; CR, composite reliability; AVE, average variance extracted.

the identification of multiple configurations (combinations) of causal conditions that can lead to high supply chain performance. After cleaning the survey data, principal component analysis (PCA) was first used to validate and reduce the number of items under each variable by identifying components with strong factor loadings. For each causal condition, the retained component scores were used as the basis for calibration in the fsQCA 4.1 software. Calibration involved transforming the continuous component scores into fuzzy set membership values ranging from 0 (full non-membership) to 1 (full membership), by using the inbuilt calibrate function '*Calibrate (x; n1; n2; n3)*' where 'x' is the variable to be calibrated, 'n1' is the maximum value, 'n2' is the mean and 'n3' is the minimum value given in the descriptive statistics of the constructs. This process ensured standardisation and allowed for constructing the truth-table, from which consistent and empirically supported causal configurations were derived to explain the high and low LSCP.

Results

Discussion

The demographic profile of the respondents engaged in the Indian millet supply chain, given in Table 2, reveals a predominantly male workforce, reflecting the traditionally male-dominated nature of agricultural logistics and distribution sectors. Most respondents are between 30–50-years-old, indicating a mature, professionally active demographic with practical experience in agri-business. A significant share (53.8%) reported 4–8 years of experience in the millet supply chain, suggesting a reasonable level of operational familiarity and field exposure. The respondents represent diverse roles, with a noticeable concentration in positions such as FPO representatives, government agriculture officers and private sector supply chain professionals. Most are affiliated with FPOs, government agencies and private enterprises, highlighting the collaborative but fragmented millet

TABLE 2: Demographics profile of the respondents (N = 132).

Variable	Category	*n*	%
Gender	Male	92	69.7
	Female	40	30.3
Age (years)	< 30	28	21.2
	30–40	44	33.3
	40–50	37	28
	> 50	23	17.4
Designation or role	FPO Representative	25	18.9
	Procurement Officer	10	7.6
	Warehouse Manager	8	6.1
	Distributor/Wholesaler/Retailer	15	11.4
	Supply Chain Manager	11	8.3
	Agriculture Officer	20	15.2
	Agri-Tech Service Provider	7	5.3
	Marketing Executive	5	3.8
	Cooperative Society Representative	7	5.3
	Processing Unit Manager	6	4.5
	Logistics Coordinator	5	3.8
	Quality Assurance Officer	5	3.8
	Others	8	6.1
Organisation type	FPO	40	30.3
	Government	35	26.5
	Private	33	25
	NGO	10	7.6
	Cooperative	9	6.8
	Others	5	3.8
Years of experience	< 3	38	28.8
	4–8	71	53.8
	> 8	23	17.4
Region	Odisha	41	31
	Andhra Pradesh	45	34.1
	Karnataka	27	20.5
	Tamil Nadu	19	14.4

FPO, farmer-producer organisation; NGO, non-governmental organisation.

TABLE 3: Analysis of necessary conditions.

Conditions tested	Consistency	Coverage	Consistency	Coverage
TEC	0.731	0.680	0.673	0.642
FC	0.776	0.689	0.682	0.622
ML	0.852	0.751	0.614	0.556
INV	0.769	0.689	0.648	0.596
WR	0.814	0.745	0.591	0.555
STP	0.622	0.548	0.822	0.744
Outcome variable	*LSCP*		*~LSCP*	

TEC, tech-integration; FC, farmer coordination; ML, market linkage; INV, inventory control; WR, waste reduction; STP, standardised processes.

TABLE 4: Causal configurations leading to high lean supply chain performance in millet distribution.

Configurations	Raw coverage	Unique coverage	Consistency
FC*ML*~STP	0.541	0.044	0.924
~TEC*FC*WR	0.460	0.021	0.859
ML*INV*WR	0.608	0.035	0.893
FC*WR*STP	0.473	0.017	0.837
TEC*FC*ML*~INV	0.384	0.003	0.918
TEC*~FC*ML*INV	0.408	0.021	0.932
~TEC*ML*INV*STP	0.364	0.008	0.864
~TEC*ML*WR*STP	0.386	0.017	0.886
Coverage	0.869	-	-
Consistency	0.788	-	-
Consistency cutoff	0.926	-	-

Note: Model: LSCP = f(TEC, FC, ML, INV, WR, STP).

TEC, tech-integration; FC, farmer coordination; ML, market linkage; INV, inventory control; WR, waste reduction; STP, standardised processes.

*denotes the combination of conditions; ~ indicates the absence or low presence of a condition.

distribution in India. Geographically, the study focused on the south-eastern states, including Odisha, Andhra Pradesh, Tamil Nadu and Karnataka. Most respondents are from Andhra Pradesh and Odisha, making it nearly 65% of the total sample. This composition provides a balanced and contextually relevant sample for understanding the drivers and barriers to lean supply chain practices in the millet sector.

The necessity analysis given in Table 3 shows that none of the individual conditions meet the conventional threshold of 0.90 consistency (Ragin & Davey 2022), indicating that no single factor is strictly necessary for achieving or failing to achieve high/low LSCP. Among the tested conditions, ML (consistency = 0.852, coverage = 0.751) and WR (consistency = 0.814, coverage = 0.745) come closest to being necessary for high LSCP, suggesting they are the most consistently associated with strong outcomes. For low LSCP (~LSCP), STPs (consistency = 0.822, coverage = 0.744) emerge as a prominent factor, implying that weak or inconsistent standardisation is often present when performance is poor. These findings highlight that while no single variable guarantees outcomes on its own, ML and WR function as critical enabling conditions for high performance, whereas deficiencies in STP strongly align with low performance. This supports the fsQCA principle that performance in complex supply chains arises from configurations of conditions rather than any one factor alone.

The truth-table analysis was conducted in fsQCA 4.1 using the intermediate solution, which is recommended as the primary output as it balances empirical evidence with theoretically informed counterfactuals (Ragin 2018). The fsQCA results in Table 4 provide all combinations of conditions that lead to high LSCP. With a solution consistency of 0.788 and a solution coverage of 0.869, the model indicates strong explanatory value and acceptable logical consistency per methodological standards (Schneider & Wagemann 2009) of the fsQCA model. In other words, this suggests that approximately 87% of the cases leading to high LSCP have been captured by the configurations identified in this solution set, with each pathway being consistent with the observed results.

The configuration FC*ML*~STP indicates strong farmer coordination and robust ML, with lower logistical process standardisation associated with high lean performance. In India, standardised operational practices are often lacking or inconsistent across agricultural supply chains, especially in unorganised rural market systems (Carrijo et al. 2024). However, strong coordination with farmers and market access helps offset the lack of standardisation by facilitating smoother demand–response mechanisms and reducing information asymmetry (Diwakar et al. 2023). This finding aligns with the emphasis of LSCM theory on responsiveness and flow optimisation. However, it extends the theory by showing that in fragmented agri-food markets, relational mechanisms such as farmer coordination and ML can substitute for formalised process standardisation. Therefore, it suggests efforts to enhance direct relationships between farmers and buyers, contributing to lean outcomes without strong formalised standard procedures.

Interestingly, configuration ML*INV*WR reflects the operational reality of the Indian agri-sector, where effective inventory management is essential to minimise post-harvest losses and respond to fluctuating demand. This finding supports the LSCM principle of WR as a driver of lean outcomes, while also demonstrating that its effectiveness depends on complementary practices such as inventory control, highlighting the contingent rather than universal nature of lean enablers. Prior studies similarly highlight the role of inventory infrastructure in enhancing supply chain performance in agriculture (Chistnikova et al. 2021; Khalid & Ndolo 2024). The emphasis on WR further aligns with Chairany et al. (2022), who developed a lean-risk matrix to mitigate food loss in the Indonesian cayenne pepper supply chain, offering insights that are equally applicable to Indian millet supply chains, where crop loss during harvesting, storage and transport remains a persistent challenge.

The configurations TEC*FC*ML*~INV and TEC*~FC*ML*INV indicate that high technology integration strengthens lean outcomes when integrated with other variables such as ML and farmer coordination. On the contrary, configurations such as ~TEC*ML*INV*STP and ~TEC*ML*WR*STP also lead to high performance, indicating that technology is not necessary but can be a sufficient enabler when used in coordination with other practices. Many studies in the Indian context claim that technology integration in the supply chain is a significant enabler of its performance (Ganbold et al. 2021; Gupta et al. 2021; Ruzo-Sanmartín et al. 2024). However, the minimal use of technology is in practice in the agri-supply chain sector in the Indian context (Gupta et al. 2021). Still, the use of advanced technology is critical and requires infrastructure and adoption at the grassroots level. Per Tiwari et al. (2021), technology adoption in Indian agriculture is still fragmented, especially among the farmers. Therefore, focusing on capacity building, awareness and access to affordable digital solutions could help lean performance where technology is missing. From the theoretical standpoint, this observation highlights the configurational extension of LSCM theory where technology is not an independent driver of lean outcomes but operates as a contingent capability whose effect varies depending on other conditions. This asymmetry challenges linear interpretations of LSCM and situates it within a complexity-informed framework.

Another configuration, FC*WR*STP, with a raw coverage of 0.473, indicates that lean performance can also be achieved when farmer coordination is paired with WR and STPs. Similarly, the configuration ~TEC*FC*WR also leads to high LSCP with a raw coverage of 0.460, indicating the significant role of farmer coordination and WR. This observation is supported by Vostriakova et al. (2021), who applied VSM to optimise logistics and eliminate redundancy in agri-food chains. It also emphasises the synergistic effect of coordination and process alignment, particularly in decentralised supply chains. Overall, the fsQCA model exhibits that there is no single path to achieving high LSCP in the millet supply chain — the study area. Instead, it results from multiple, context-specific combinations of practices that allow us to accept proposition 1. Variables such as ML, inventory control, WR and farmer coordination are consistently influential. In contrast, technology and standardisation play complementary roles, enhancing but not necessarily guaranteeing higher performance in the prevailing scenario.

The second fsQCA truth-table presented in Table 5 exhibits the configurations leading to low LSCP. The solution coverage and consistency are 0.802 and 0.863, respectively, with a consistency cutoff value of 0.933. The strongest pathway ~ML*~WR, with a raw coverage of 0.579, shows that when both ML and WR are weak, LSCP deteriorates sharply. In India, farmers often lack direct access to urban markets, and post-harvest losses remain high because of inadequate cold chains and poor handling practices. This supports prior findings that emphasise reducing food waste at upstream supply chain levels through stronger coordination and logistics infrastructure (Chairany et al. 2022; Kharola et al. 2022). Similarly, the configuration ~INV*~WR*STP indicates that even with some STPs, the absence of inventory control and WR mechanisms leads to poor performance, confirming that standardisation alone cannot compensate for fundamental operational gaps (Khalid & Ndolo 2024). Addressing these challenges requires well-structured inventory systems and improved storage infrastructure, particularly in the millet sector.

The third combination, ~TEC*~ML*STP, indicates that even with STPs, poor technology integration and market connectivity limit efficient supply chain performance. This scenario is common in rural India, where smallholders operate with minimal technology exposure, leading to tracking, forecasting and delivery inefficiencies. Better ML is highly reliant on the adoption of technology. So, the lack of technology integration also affects the market access, leading

TABLE 5: Causal configurations leading to low lean supply chain performance in millet distribution.

Configurations	Raw coverage	Unique coverage	Consistency
~ML*~WR	0.579	0.072	0.915
~INV*~WR*STP	0.474	0.033	0.936
~TEC*~ML*STP	0.436	0.002	0.915
TEC*FC*~ML*~INV	0.310	0.016	0.938
~TEC*FC*~INV*STP	0.339	0.009	0.913
~TEC*~FC*INV*STP	0.321	0.033	0.935
~FC*~ML*INV	0.355	0.013	0.923
TEC*~ML*INV*~STP	0.289	0.001	0.899
Coverage	0.802	-	-
Consistency	0.863	-	-
Consistency cutoff	0.933	-	-

TEC, tech-integration; FC, farmer coordination; ML, market linkage; INV, inventory control; WR, waste reduction; STP, standardised processes.

Model: ~LSCP = f(TEC, FC, ML, INV, WR, STP).

to poor business performance. Contrarily, the combination TEC*FC*~ML*~INV demonstrates that even when technology is present and farmer coordination is strong, lean outcomes are not achieved if the technology fails to enhance ML and inventory control. It reflects situations in which even tech-savvy FPOs struggle with storage, pricing and timely market access, leading to inefficiencies. The effectiveness of technology integration depends on collective adoption across supply chain actors rather than isolated efforts (Gupta et al. 2021; Ruzo-Sanmartín et al. 2024). It is consistent with Elbarky et al. (2025), who argue that structural gaps within the system can undermine lean adoption despite localised or individual capabilities. The configuration ~TEC*FC*~INV*STP shows that weak technology use and inventory control result in poor outcomes, even when farmer coordination and standardisation are present. Similarly, ~TEC*~FC*INV*STP indicates that lean performance remains constrained when technology and coordination are absent despite stronger inventory management. The combinations ~FC*~ML*INV and TEC*~ML*INV*~STP confirm that no single factor guarantees performance in isolation. Across these pathways, common weaknesses such as limited ML, inadequate inventory systems, poor waste management and low technology adoption consistently emerge as key drivers of poor outcomes. This underscores that in the Indian millet context, LSCP collapses when fundamental capabilities are missing, regardless of the presence of secondary enablers such as coordination or standardisation (Chairany et al. 2022; Chistnikova et al. 2021).

Implications

This study gives a detailed insight to the stakeholders and supply chain members willing to enhance lean performance and profitability. These observations support the objectives of the National Mission on Millets, which emphasises empowering FPOs and improving market integration for smallholders. Thus, FPOs, cooperatives and various private and public sector organisations can benefit from these insights to build stronger farmer-market interfaces, reduce information asymmetries and streamline demand–response time. For smaller FPOs with limited technological capacity, support should focus on ML, decentralised storage and training in WR, as these pathways emerged as sufficient for high performance. Larger processors and organisations with digital capacity, on the other hand, should prioritise traceability, demand forecasting and integrated procurement systems, where technology acts as an amplifier of lean practices. Across both groups, policy incentives, training and investment in warehousing and cold chain infrastructure can reduce post-harvest losses and improve responsiveness. In addition, the significant role of inventory control and WR in high-performance pathways suggests that government and logistics members should prioritise investments in decentralised storage, low-cost warehousing and cold chain infrastructure development. Differentiating interventions in this way ensures that policy and managerial recommendations remain practical and closely aligned with the resource endowments identified in the configurational analysis.

Conclusion

The study shows that LSCP does not stem from any single factor but from diverse configurations of practices. Market linkage, WR and inventory control consistently emerge as critical components of high-performance pathways, while technology and standardisation, although beneficial, are not always necessary when other strengths compensate. Conversely, low performance is linked to weak market access and poor inventory and WR, regardless of technology use or process standardisation. By integrating LSCM with the Configurational Approach to Causal Complexity, the study advances theory by demonstrating that lean principles operate through context-specific bundles shaped by infrastructure constraints and institutional fragmentation. This contributes to embedding LSCM in a complexity-informed framework and shows the utility of configurational analysis for theorising supply chain management in low-resource agri-food systems. Empirically, the findings suggest that achieving lean supply chain goals in millet distribution requires a multidimensional, context-sensitive strategy rather than one-size-fits-all prescriptions.

Limitations

This study has a few limitations that need to be discussed in detail to uncover the future scope of research in this subject. Firstly, the study is context specific, exclusively concentrating on millet supply chains, which may limit the generalisability of findings to other agricultural products or regions in India. As such, the sample size, though adequate for fsQCA analysis, remains relatively modest and may not capture the full diversity of stakeholder experiences. Secondly, response bias is possible, as respondents may have over- or under-reported their practices and experiences with the supply chain because of social desirability or the lack of awareness. As such, possible biases may arise from the overlapping experiences with supply chain practices in other agricultural products, which may have influenced their perceptions and responses related specifically to millet supply chains. Moreover, in terms of measurement, the reliance on self-reported survey data may not fully capture actual practices. Although calibration was carefully implemented, alternative operationalisations of conditions might yield slightly different configurational patterns. Thirdly, the findings may be context specific as the sample is skewed towards respondents from Andhra Pradesh and Odisha and over-represents FPOs and government actors, which limits generalisability beyond the studied regions and organisational types. Future research could address these gaps by increasing the sample across more diverse agro-climatic regions, incorporating real-time quantitative data and combining qualitative insights with configurational analysis.

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Authors' contributions

N.M. contributed to the conceptualisation, methodology, software development and prepared the original draft. M.U. and B.P. conducted the investigation and formal analysis and contributed to visualisation. A.K.P. contributed to validation and project administration and supported resource mobilisation alongside S.K.C. and S.R.D. The authors, B.P. and S.R.D., were responsible for data curation. S.K.C. supervised and also collaborated with N.M. on the original draft and with A.K.P. and S.R.D. on resource management. V.S. contributed to the writing, review and editing. All authors reviewed and approved the final version of the manuscript.

Ethical considerations

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Data availability

The data that support the findings of this study are not openly available because of reasons of sensitivity and are available from the corresponding author, N.M., upon reasonable request.

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