



ENVIRONMENTAL COSTS OF SUPPLY CHAIN INEFFICIENCIES IN THE INDONESIAN POTATO AGRO-INDUSTRY: A HYBRID SITUATIONAL ANALYSIS WITH LIFE CYCLE ASSESSMENT

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ABSTRACT

Modern agricultural supply chains often emphasize sophistication over resilience, a strategy that backfires in regulated developing economies. This study investigates the environmental implications of structural mismatches in the Indonesian potato agro-industry, comparing the import-dependent Industrial Stream (Stream A) and the fragmented Local Stream (Stream B). Using a mixed-methods approach combining Situational Analysis and Gate-to-Gate Life Cycle Assessment (LCA), this work identifies the "Inventory Paradox." Results show that Stream A fails under regulatory pressure, forcing a Make-to-Stock shift where emissions spike to 2,659.99 kg CO₂eq/ton—6.4% higher than the low-tech Stream B (2,500.80 kg CO₂eq). This inefficiency stems from a "double penalty" of cooling loads and material degradation, whereas Stream B benefits from energy-free logistics. To address this, the study proposes an Integrated Circular FSCN as a conceptual model introducing an Intermediate Valorization Center to recycle local tubers. This framework theoretically decouples the industry from import volatility while potentially reducing carbon intensity within the network. Findings suggest that in tropical contexts, circularity and logistics speed determine sustainability more than machine efficiency.



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I. INTRODUCTION

Modern agricultural supply chains face a paradoxical challenge: ensuring food security often comes at the expense of planetary boundaries. This tension is particularly evident in the tuber processing sector, where energy-intensive logistics clash with perishable supplies. Potatoes (*Solanum tuberosum* L.) have emerged as a strategic crop for the future. According to [1], potatoes are not only the third most important food crop globally but also play an important part in poverty alleviation and nutritional stability in developing countries due to their adaptability and high caloric density. However, this potential is hampered by very high levels of Food Loss and Waste (FLW). A recent systematic review indicates that FLW contributes approximately 8–10% to global greenhouse gas (GHG) emissions, a figure that demands urgent mitigation strategies [2]. This challenge is particularly acute in the tuber processing sector. Potato starch, a vital hydrocolloid widely used as a texture enhancer, binder, and thickener in foods [3], requires rigorous processing that is energy and resource-intensive. The transition from raw tubers to industrial starch involves a complex value chain where physical losses are often compounded by socio-economic frictions. When potatoes are lost or rejected before processing, the environmental costs are multiplied: the "sunk costs" of emissions from cultivation (fertilizer, fuel, land use) and additional emissions arising from waste disposal [4]. Decoupling potato processing from environmental degradation requires more than just technological improvements; it demands a systemic analysis of the supply chain inefficiencies that drive these losses. Indonesia presents an interesting case study in this agro-industry dilemma. As a leading potato producer in Southeast Asia, centered in highland areas such as Dieng, Pangalengan, and Batu, the country has significant agronomic potential. However, the sector is plagued by a "competitiveness paradox." Despite high harvest volumes, the domestic agro-industry remains heavily dependent on imports of starch and processed products [5].

In turn [6] argue that while Indonesian potatoes have a comparative advantage in terms of demand, they lack a competitive advantage due to high input costs, price volatility, and inconsistent tuber quality. This gap creates a "missing middle," a structural void where local supply fails to meet industry specifications. The supply chain landscape is highly heterogeneous. On the one hand, [7] show that structured partnerships, such as the one in Magelang (PT Agro Lestari Merbabu), can achieve high performance in terms of reliability and responsiveness through the implementation of Supply Chain Operations Reference (SCOR) standards. On the other hand, much of the sector remains fragmented. By [8] describe networks dominated by multi-layered chains of intermediaries in regions like Wonosobo, where information asymmetries prevent farmers from understanding market requirements. Despite isolated pockets of efficiency, the broader industry faces a chronic shortage of quality raw materials. Although national statistics indicate a surplus in raw tuber production, systemic gaps persist at the industry interface. Preliminary information gathered from senior industry experts reveals the grim reality of a supply-demand imbalance. Informant E-4, a senior potato-based product development expert with over three decades of experience in the multinational snack food manufacturing industry, revealed that large-scale processing facilities in Indonesia frequently face raw material shortages, requiring potato starch imports—up to 3 tons per day per plant—to maintain operational continuity [9].

This reliance on imports is not merely a quantity issue but a quality one. Informant E-5, R&D Manager with over 20 years of experience in the food sector, highlighted that local sourcing is financially risky due to the high variability in material properties, which directly impacts the Cost of Goods Manufactured (COGM). He emphasized that without rigorous quality control, the 'loss impact to cost' becomes unsustainable for modern manufacturing standards. The domestic agro-industry is paradoxically facing a raw materials shortage despite being located in a major potato-producing nation. A key shortcoming of existing literature is the tendency to treat supply chain inefficiencies and environmental impacts in isolation. Agronomic studies often focus on technical yield determinants, such as seed varieties and pest management [10]. Meanwhile, performance measurement studies—such as the work by [7], [11]—focus primarily on economic metrics like gross margins and delivery reliability. While these contributions are valuable, they rarely quantify the environmental consequences of the identified managerial failures. Recent empirical evidence suggests that the root causes of physical waste in Indonesia are deeply socio-economic. By [12] reveal a pattern of "farmers' dependency" in the Batur-Dieng region, where smallholders are locked into bonded relationships with collectors due to capital constraints. This dependency erodes bargaining power and creates a "trust deficit," discouraging investment in high-quality inputs like G0 seeds. The repercussions are severe: low-quality seeds lead to tubers with low specific gravity, resulting in rejection rates at the factory gate that can exceed 15-20% [13].

Here lies the primary research gap: No study has yet integrated the dynamics of behavioral drivers—specifically the "trust deficit" and "side-selling"—with the consequent environmental burden (Carbon Footprint). There is a lack of empirical understanding of how socio-economic friction translates into kilograms of CO₂ equivalent emissions through the mechanism of product rejection and logistical inefficiency. Addressing these inefficiencies requires assessing alternative pathways for utilizing "sub-standard" potatoes. Currently, the dichotomy lies between centralized industrial processing (which offers high efficiency but demands high quality and long-distance transport) and traditional markets. However, emerging literature points to the potential of decentralized valorization. According to [2], [14] emphasize the role of waste valorization in circular bio-economies. Technologies ranging from simple solar drying at the village level [15] to microwave-assisted drying [16] offer potential solutions to reduce physical loss. However, the environmental impact of these decentralized models compared to centralized industrial pathways remains under-quantified in the Indonesian context. This study aims to bridge the gap between supply chain management and environmental engineering by adopting a hybrid methodological framework. By integrating Situational Analysis based on the Food Supply Chain Network (FSCN) model with a Gate-to-Gate Life Cycle Assessment (LCA), this research provides a comprehensive diagnosis that links root causes (network structure, management, resources) to environmental outcomes (Global Warming Potential, energy use). Specifically, this article addresses three primary objectives:

1. To diagnose the structural, behavioral, and managerial drivers of inefficiency across Indonesia's key potato clusters (Dieng, Pangalengan, Batu) and the industrial processing sector, concentrating on the consequences of trust deficits, market fragmentation, and regulatory inventory dilemmas.
2. To quantify the environmental impacts (Carbon Footprint) of import-reliant industrial supply chains compared to alternative local supply and valorization scenarios.
3. To propose integrated mitigation strategies that align economic competitiveness with environmental sustainability, offering a decoupling pathway to decarbonize the agro-industry in emerging markets.

This paper therefore, takes a diagnostic position. It does not attempt to optimise a supply chain or evaluate a policy intervention. Instead, it combines a situational analysis grounded in the Food Supply Chain Network (FSCN) framework with a gate-to-gate Life Cycle Assessment (LCA) to examine how structural, managerial, and behavioural frictions in the Indonesian potato agro-industry materialise as environmental burdens. Particular attention is given to inventory buffering under regulatory uncertainty, a practice that appears operationally rational but proves environmentally costly. On the basis of the mechanisms identified, an Integrated Circular FSCN is presented as a design proposition to address the diagnosed inefficiencies. The operational performance of this proposed configuration is not assessed in this paper and is left for future research.

II. MATERIALS AND METHODS

This study uses a mixed-method research design, integrating a qualitative Situational Analysis based on the Food Supply Chain Network (FSCN) framework with a quantitative Life Cycle Assessment (LCA). This hybrid approach enables a comprehensive diagnosis that links structural supply chain inefficiencies (the "causes") to their environmental consequences (the "effects").

II.1 STUDY AREA AND SITE CHARACTERIZATION

The research was conducted in three distinct functional clusters in Java, Indonesia, selected to represent the heterogeneity of supply chain configurations and agro-ecological performances (Figure 1).

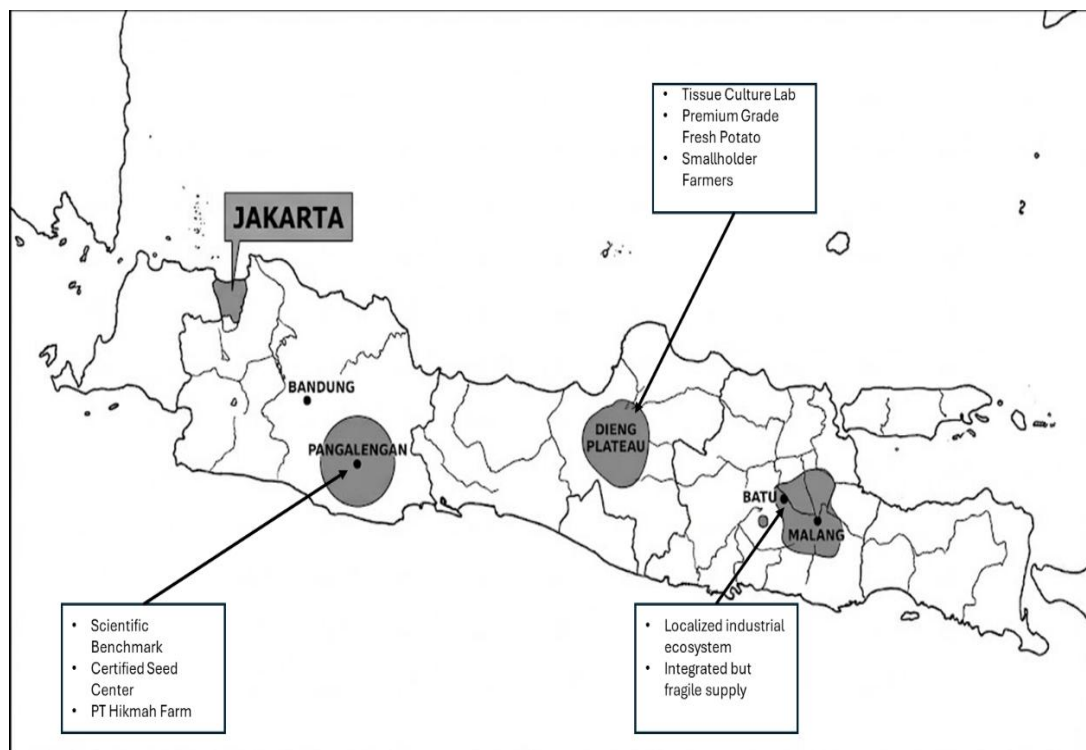


Figure 1: Characteristics of potato agro-ecological zones in Indonesia.
Source: Authors, (2026).

Pangalengan (West Java) is characterized as The Scientific Benchmark. Located at 1,400–1,500 masl, this cluster represents the pinnacle of agronomic efficiency in Indonesia. The site is anchored by PT Hikmah Farm, a strategic partner for industrial supply chains led by expert agronomists. Uniquely, this site successfully adapts Dutch cultivation technologies to tropical highlands, achieving yields of 45 tons/ha—more than double the national average. In this study, Pangalengan serves as the "Scientific Benchmark," representing the theoretical minimum environmental footprint achievable when Global Good Agricultural Practices (GlobalGAP) are strictly implemented [17], [18]. Dieng Plateau (Central Java) is characterized The Dual-Hub Paradox. Ideally situated at >2,000 masl, this region functions as a dual-purpose hub, producing both premium fresh potatoes ("Dieng Super") and certified seeds. Unlike typical fragmented clusters, Dieng possesses localized high-tech capabilities, hosting modern tissue culture laboratories (Adhiguna Farm) and national seed assessors. However, a critical paradox exists: despite these "islands of excellence," the wider context of smallholder farming remains inefficient, characterized by rampant over-fertilization [19] and oligopsonistic market structures [20]. This site represents the "Locus of the Problem," where high rejection rates (15%) and environmental degradation coexist with advanced local technology. Batu (East Java) is characterized as The Integrated Agro-Industrial Cluster. Selected as the downstream hub, Batu represents a localized industrial ecosystem where cultivation and processing are geographically integrated. Unlike Dieng's long-haul logistics, processors in this region (e.g., UD Rimbaku and Agronas) source specific processing varieties (Atlantic) from local farmers via a short supply chain (<15 km). While logistically efficient, this cluster faces distinct challenges: upstream farmers often operate below technical efficiency [21], and the SME industry is vulnerable to significant supply discontinuity and operational risks [22]. In this case, Batu serves as the case study for an "Integrated but Fragile" supply chain model.

II.2 DATA COLLECTION AND TRIANGULATION PROTOCOL

To ensure a comprehensive diagnosis of the supply chain inefficiencies, this study uses a Multi-Source Triangulation strategy, combining expert knowledge elicitation with a synthesis of recent micro-empirical studies. The data sources are stratified into two layers.

II.2.1 Tier 1: Primary Expert Elicitation (The 'Ideal' Baseline)

In-depth semi-structured interviews supported by field observations were conducted with six key informants selected through purposive sampling to capture high-level technical expertise within the Indonesian potato supply chain between November 2023 and December 2025. Anonymity was assured to promote open discussion of sensitive operational issues, including coordination challenges and product rejection practices. Informants were selected based on defined criteria: a minimum of ten years of sector experience, leadership or decision-making roles within their respective clusters, and/or formal recognition by national agricultural or industry institutions. The composition of the expert panel is summarized in Table 1. The expert group comprised both upstream and downstream supply chain actors. Upstream participants included lead farmers, seed breeders, and aggregators located in Dieng and Pangalengan ($n = 3$), providing insight into cultivation practices, seed sourcing, post-harvest handling, and rejection dynamics. Downstream participants consisted of industrial managers and product development specialists from starch-processing facilities and snack manufacturing firms ($n = 3$), contributing detailed information on raw material acceptance criteria, production losses, and industrial demand characteristics. Together, the panel was used to define technical best-practice conditions and to validate key Life Cycle Inventory (LCI) parameters applied in the environmental assessment.

Table 1: Experts profile matrix.

Code	Role / Position	Key Qualifications	Cluster
E-1	Senior Agronomist & Farm Director	M.Sc. in Agronomy from Wageningen University; >20 years exp. In adapting European cultivation systems to tropical highlands. Achieved productivity benchmarks of >40 tons/ha.	West Java (Pangalengan)
E-2	Tissue Culture Specialist & Farm Owner	M.Sc. in Biology from Gadjah Mada University; Owner of a private in-situ tissue culture laboratory; Pioneer in G0 seed acclimatization for local smallholder farmers.	Central Java (Dieng)
E-3	Farm Owner, Senior Aggregator & Seed Assessor	Appointed as National Seed Certification Assessor by Ministry of Agriculture; Manages >50 ha of plasma partnership.	Central Java (Dieng)
E-4	Product Development Expert	>30 years exp. in multinational snack companies; Specialist in potato starch application and texture profiling.	National / Industrial
E-5	R&D Manager (Food Industry)	>20 years exp. in Food Manufacturing; Specialist in COGM (Cost of Goods Manufactured) and material loss analysis.	National / Industrial
E-6	Supply Chain Manager (Food Industry)	>10 years exp. in Food Manufacturing; Specialist in potato chips gate-to-gate logistics.	National / Industrial

Source: Authors, (2026).

The size of the expert panel reflects the specialized nature of technical decision-making within the Indonesian potato sector, where a limited number of actors hold system-level knowledge across cultivation, aggregation, and industrial processing. Consistent with expert elicitation practices, emphasis was placed on depth of experience rather than numerical representation. Interviews were conducted until thematic saturation was reached, with later discussions confirming previously identified structural and operational constraints. The expert inputs were used primarily to validate network configurations, behavioral drivers, and Life Cycle Inventory parameters rather than to infer population-level trends. These expert consultations provided contextual validation for the structural and behavioral constraints incorporated into the analytical framework. Evidence of persistent trust-related barriers to formal contracting emerged from interviews with Informant E-2, who described socio-cultural skepticism among smallholders toward corporate partnerships, noting that “villagers have a specific stigmatized image when big companies arrive... questioning their true motives” [23]. This perspective informed the representation of transactional frictions within the situational analysis.

At the aggregation stage, Informant E-3 confirmed the rejection parameters applied in the Life Cycle Inventory (LCI), explaining that strict industry requirements for specific gravity (SG) frequently lead to the exclusion of tubers that are visually acceptable. He observed that “perfectly good potatoes are often returned simply for failing SG specs,” resulting in substantial economic losses at farm level, while also highlighting the potential reuse of rejected produce for alternative flour applications (“It is actually highly potential”) [24]. Industrial-level constraints were further clarified by Informant E-6, who identified a disconnect between available domestic supply and industrial utilization. Despite periods of surplus biomass, regulatory standards and chemical quality thresholds, particularly related to sugar content, limit procurement and necessitate continued reliance on imports. This evidence supported the biological and regulatory constraints incorporated within the downstream LCA scenarios [25]. Finally, Informant E-1, representing high-efficiency production systems, attributed limited technology adoption among smallholders primarily to behavioral factors rather than input availability. He noted that “farmers are accustomed to being followers with minimal independent research,” which contributes to slow uptake of standardized operating procedures demonstrated in the Pangalengan cluster [18].

II.2.2 Tier 2: Micro-Empirical Data Synthesis (The 'Actual' Reality)

Rather than administering an additional generic survey, the operational behavior and constraints of smallholder actors, including farmers, collectors, and transport providers, were derived through a synthesis of site-specific empirical studies conducted in the study regions between 2021 and 2025. This approach was adopted to ensure that the parameters reflect post-pandemic operating conditions and locally observed practices. Several datasets were integrated to characterize network performance. Information on logistical delays and points of product loss within the Dieng production cluster was obtained from a prior Value Stream Mapping analysis [13]. Socio-economic parameters related to farmer dependency patterns and coordination challenges in the Batur–Dieng area were drawn from earlier field-based research [12]. In addition, governance-related performance differences between fragmented and more structured supply chain arrangements were synthesized from comparative empirical studies [7], [8]. By combining these sources, the analysis contrasts modeled technical efficiency (Tier 1) with empirically observed system behavior (Tier 2), allowing for a quantification of the environmental implications arising from operational gaps.

II.3 SITUATIONAL ANALYSIS: DIAGNOSING THE NETWORK STRUCTURE

To examine the organization and functioning of the potato supply chain, this study applied the Food Supply Chain Network (FSCN) framework proposed by [26]. The framework was used as a diagnostic tool to describe the system across four interrelated dimensions: network structure, chain business processes, chain management, and resources. Data reliability was strengthened through triangulation by comparing interview transcripts with field observations and secondary sources, including agronomic information from *Tentang Kentang* [27].

II.3.1 Network Structure

The physical flow of potatoes was mapped from seed producers to industrial processors in order to identify key actors, their roles, and points of fragmentation within the network, including the presence of structural gaps commonly referred to as the “missing middle”.

II.3.2 Chain Business Process

Operational activities along the chain, such as grading, storage, and transportation, were examined to identify process-level inefficiencies. Value Stream Mapping (VSM) results from a previous study [13] were used to highlight non-value-added activities, particularly prolonged waiting times at collection centers in the Dieng production area.

II.3.3 Chain Management

Governance arrangements within the network were assessed with attention to contract practices, grading standards, and the degree of coordination and trust among supply chain actors.

II.3.4 Resources

The analysis considered both tangible inputs, such as access to certified G0 seed material, and intangible factors, including bargaining power and information access, that influence production and transaction outcomes.

II.4 LIFE CYCLE ASSESSMENT (LCA)

A gate-to-gate Life Cycle Assessment was conducted in accordance with ISO 14040/14044 standards. This specific boundary selection allows the study to isolate the environmental performance of supply chain logistics and industrial processing technologies from the high variability of agronomic practices. This study assesses only post-harvest and industrial stages; upstream impacts are discussed qualitatively and not part of the LCA results. The assessment was modeled using OpenLCA software (version 2.3.0), and the impact is estimated according to the TRACI 2.1 method. The primary goal is to quantify the environmental burden associated with post-harvest handling, logistics, and processing inefficiencies, specifically focusing on the trade-offs between imported and local supply and its valorization pathways. As illustrated in Figure 2, the system boundary delineates two distinct, non-intersecting operational streams that characterize the structural dichotomy of the Indonesian potato agro-industry. The first pathway, identified as the Industrial-Import Line (Stream A), represents the modern industrial mechanism modeled based on Informant E-6. The boundary for this stream initiates at the Port Gate of Origin, where imported tubers enter the logistics chain. It then encompasses the critical Industrial Storage stage—where the "Inventory Paradox" and its associated energy burdens are quantified—and concludes at the Factory Gate following the high-tech continuous frying process. Parallel to the industrial line, the second pathway is identified as the Traditional-SME Line (Stream B), representing the local traditional supply chain modeled based on Informant E-3 and Tier-2 data from the Batu SME cluster. For this stream, the boundary commences at the Farm Gate in the Dieng highlands, proceeds through the aggregation and manual sorting stages, and terminates at the SME Gate following the traditional batch frying process. To ensure comparability between these divergent scales, the study adopts a Functional Unit (FU) of 1,000 kg of finished potato chips. This specific scale provides a standardized baseline to contrast the mass-production capabilities of the industrial line against the aggregated output of the SME cluster, thereby highlighting the magnitude of inefficiencies present in both streams.

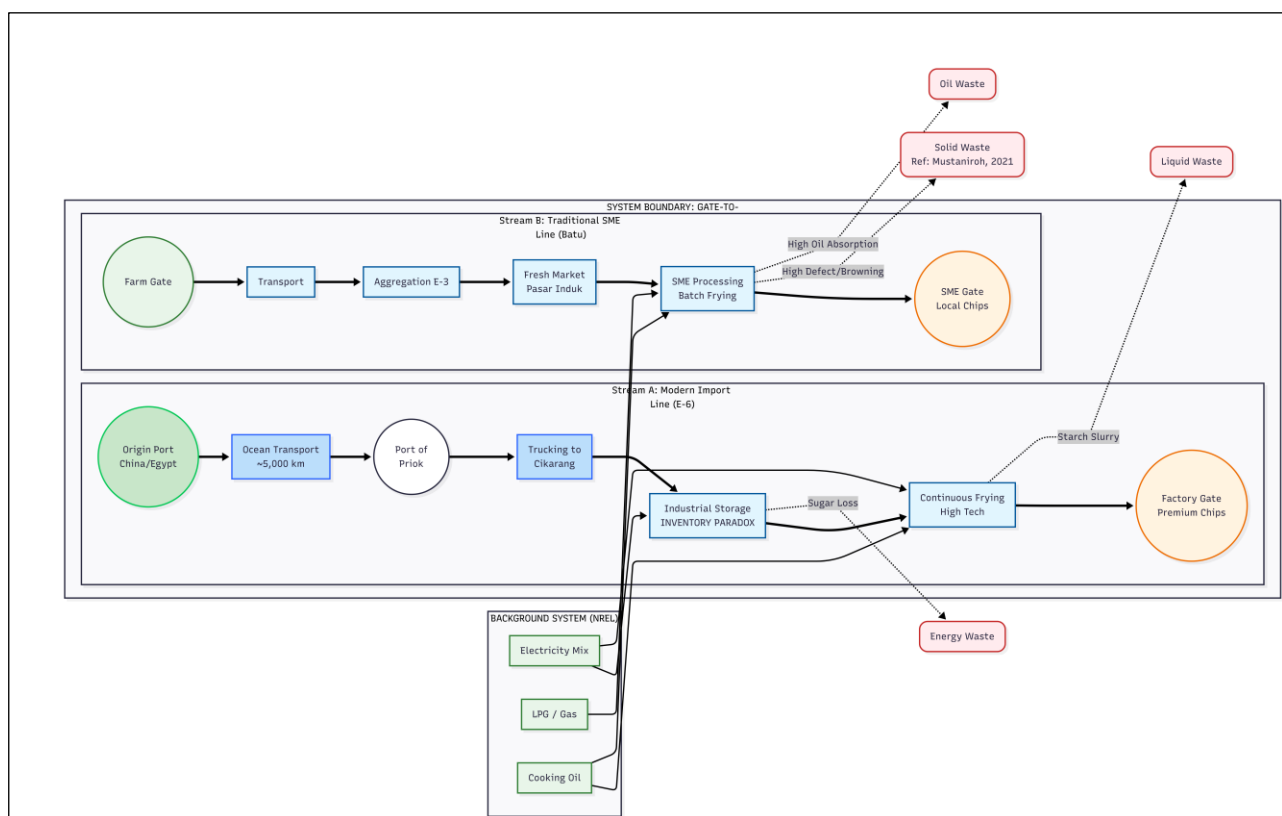


Figure 2: System Boundaries of Life Cycle Assessment.
Source: Authors, (2026).

LCI is the most complex stage in the LCA methodology, because LCA practitioners often have to deal with problems with missing inventory data [28], so a series of assumptions are made to obtain the most detailed inventory possible. Regarding the data inventory, the foreground system was modeled using primary data collected from in-depth interviews and direct field observations. The background system utilizes secondary data from the NREL USLCI database with rigorous proxy adaptations. The NREL USLCI database was chosen due to its being entirely free to access, thus ensuring accessible replication for future research. The standard US electricity mix was substituted with a custom-built "Java-Bali Grid Proxy"—comprising approximately 90% fossil energy, and 10% renewables—to accurately reflect the carbon intensity of electricity consumed during the storage and processing stages in the Indonesian context. The 'Java-Bali Grid Proxy' was constructed based on the 2024 electricity generation mix data published by PT PLN (Persero) [29], which reported a coal dominance of approximately 45%, gas of approximately 37%, and diesel 8%. For this LCA model, a simplified composition of 45% bituminous coal, 37% natural gas, 8% diesel, and 10% renewable energy was adopted to represent the high-carbon baseload characteristic of the industrial storage location. Table 2 summarizes the gate-to-gate Life Cycle Inventory (LCI) data utilized in this study, modeled across three distinct supply chain scenarios to assess the environmental implications of the Inventory Paradox. Frying oil (Palm Olein) assumption was using 0.4 – 0.45 liters/kg chips [30], [31] converted into 400 kg palm olein per 1000 kg chips for simplicity. According to Sayed et al. (2023), the typical water consumption is 1.25 – 4.3 liters/kg chips; we use the assumption of 1.25 liters/kg chips.

For Stream B (Traditional SME), inventory data—specifically the material conversion ratio—was derived from empirical studies on potato chip production in Garut, West Java, which identified a product yield of approximately 26.45% relative to unpeeled fresh tubers [32]. The reference flow required to produce the functional unit (1,000 kg of chips) in Stream B was calculated at 3,781 kg of fresh potatoes. In contrast, Stream A (Industrial) is differentiated into two scenarios: the Optimal scenario (A-1), assuming a standard industrial yield of 25% (1:4 ratio) with minimal storage duration, and the Paradox scenario (A-2), which simulates supply chain disruptions driven by potato importation quota and potato chips demand fluctuation [25]. The Paradox scenario incorporates a 'double penalty' mechanism: (1) a reduced yield of 20% (necessitating 5,000 kg of input) due to quality degradation, and (2) a significant surge in energy intensity attributed to a prolonged three-month cold storage period. To ensure methodological consistency, transportation emissions for all streams were calculated based on the raw material input weight (reference flow) rather than the final product weight, thereby capturing the environmental burden associated with material inefficiency and logistical distances. The distances were measured using two approaches. Land transport distance was measured by using Google Maps to reflect the most realistic routes. Stream B route is a combination of Sumber Brantas to Batu (70% of potato source) and Dieng to Batu (30% of potato source), while Stream A route is from Tanjung Priok seaport to Cikarang, where the factory is located. Sea transport was measured through sea-distances.org using Voyage Calculator.

Table 2: Life cycle inventory for the assessment.

Input/Output Category	Parameter / Flow	Unit	Stream B (SME)	Stream A-1 (Large Scale – Optimal Inventory)	Stream A-2 (Large Scale – High Inventory)
Functional Unit	Potato Chips	kg	1,000	1,000	1,000
1. Raw Materials	Fresh Potato (Input)	kg	3,781 kg	4,000 kg	5,000 kg
	Frying Oil (Palm Olein)	kg	400	400	500
	Clean Water (Washing)	Liter	1,250	1,250	1,562.5
2. Process Energy	LPG (Thermal)	kg	97	-	-
	Natural Gas (Thermal)	MJ	-	5,000	6,250
	Electricity for Machinery (Processing)	kWh	90	112	140
3. Logistics and Storage	Warehousing Electricity (Storage)	kWh	0	156	585
	Storage Duration	Days	3 (Just-in-Time)	30 (Normal market and supply)	90 (Market and potato supply fluctuation)
4. Transportation	Sea Freight (Tianjin-Tj.Priok)	t*km	0	5,200	5,200
	Land Transport (Truck)	t*km	123	68	68
5. Output Waste	Peel Solid per 1000 kg input	kg	90	90	108
	Starch Slurry per 1000 kg input	kg	30	30	36

Source: Authors, (2026).

Process and storage energy were quantified separately for small-scale production (Stream B) and large-scale industrial lines (Stream A) to reflect differences in technology, operating scale, and inventory management. In Stream B, thermal energy was modeled using liquefied petroleum gas (LPG) for batch frying, based on measured fuel consumption reported in empirical life cycle studies of traditional potato chip producers. This corresponds to a thermal input of approximately 27,600 MJ per functional unit (1,000 kg of finished chips). Electricity use in Stream B is limited to basic processing and packaging equipment and was estimated at approximately 90 kWh per functional unit. Refrigerated storage was excluded due to near-just-in-time material turnover [33]. In Stream A, thermal energy is supplied by natural gas and allocated exclusively to heat-intensive operations, namely steam peeling, blanching, and continuous frying. Thermal inputs for the optimal inventory scenario (Stream A-1) were derived by aggregating reported industrial energy requirements for these unit operations under non-frozen crisps production, resulting in a representative natural-gas input of 5,000 MJ per functional unit.

The high-inventory scenario (Stream A-2) assumes reduced material conversion efficiency and longer residence times, leading to an increased thermal demand of 6,250 MJ per functional unit. These values represent fuel-based heat only and do not include electricity consumption [34], [35]. Electricity use in Stream A was quantified at the process level and includes grading and sorting, washing and cleaning, slicing and post-slicing sorting, auxiliary equipment associated with blanching, and post-frying cooling. Summation of these

step-level estimates yields approximately 112 kWh per functional unit for Stream A-1 and 140 kWh per functional unit for Stream A-2, consistent with reported electricity demand ranges for industrial potato crisps processing and cold-end operations [34-36]. Warehouse electricity was modeled explicitly based on the inventory configuration reported in an industry interview, which indicated that imported potatoes are stored under chilled conditions (approximately 12 °C) and may remain in storage for extended periods when demand fluctuations occur with safety stock set at 10 days of supply. Under the interview-grounded assumption that 4 t of potatoes are stored for 30 days (Stream A-1) and 5 t for 90 days (Stream A-2), a conservative specific electricity consumption factor for chilled potato storage ($0.13 \text{ kWh} \cdot \text{t}^{-1} \cdot \text{day}^{-1}$) was applied, resulting in storage electricity demands of 156 kWh and 585 kWh per functional unit, respectively [36].

III. RESULTS AND DISCUSSIONS

III.1 SITUATIONAL DIAGNOSIS: DECONSTRUCTING SYSTEMIC INEFFICIENCY VIA FSCN FRAMEWORK

To comprehensively diagnose the paradox of high aggregate production versus low industrial efficiency, this study adopted the Food Supply Chain Network (FSCN) framework developed by [26]. This diagnostic lens deconstructs the potato agro-industry into four interrelated dimensions: Network Structure (the configuration of actors), Chain Business Processes (operational activities), Chain Management (governance mechanisms), and Chain Resources (allocation of tangible and intangible assets). Our study indicates that the "systemic lock-in" responsible for environmental degradation is not monolithic but varies significantly across cluster typologies. Informant E-6 revealed that the supply-demand disconnect is primarily driven by an 'invisible quality barrier': sugar content. While farmers focus on biomass yield, industrial buyers reject tubers with high sucrose levels due to the Maillard reaction (browning) during frying. This misalignment forces large-scale industries to rely on imports despite local surplus. The FSCN-based situational analysis shows that food loss and environmental inefficiency in the potato agro-industry arose from systemic interactions across the supply chain, rather than from isolated process failures. Fragmented network structures, misaligned resource use, governance weaknesses, and inventory-driven storage practices jointly intensify quality degradation and rejection rates. These dynamics concentrate upstream environmental burdens into a smaller volume of marketable output, thereby inflating impacts per functional unit. By synthesizing these interdependencies, Figure 3 serves as a conceptual bridge linking qualitative system diagnosis with the life cycle assessment results presented in the subsequent section.

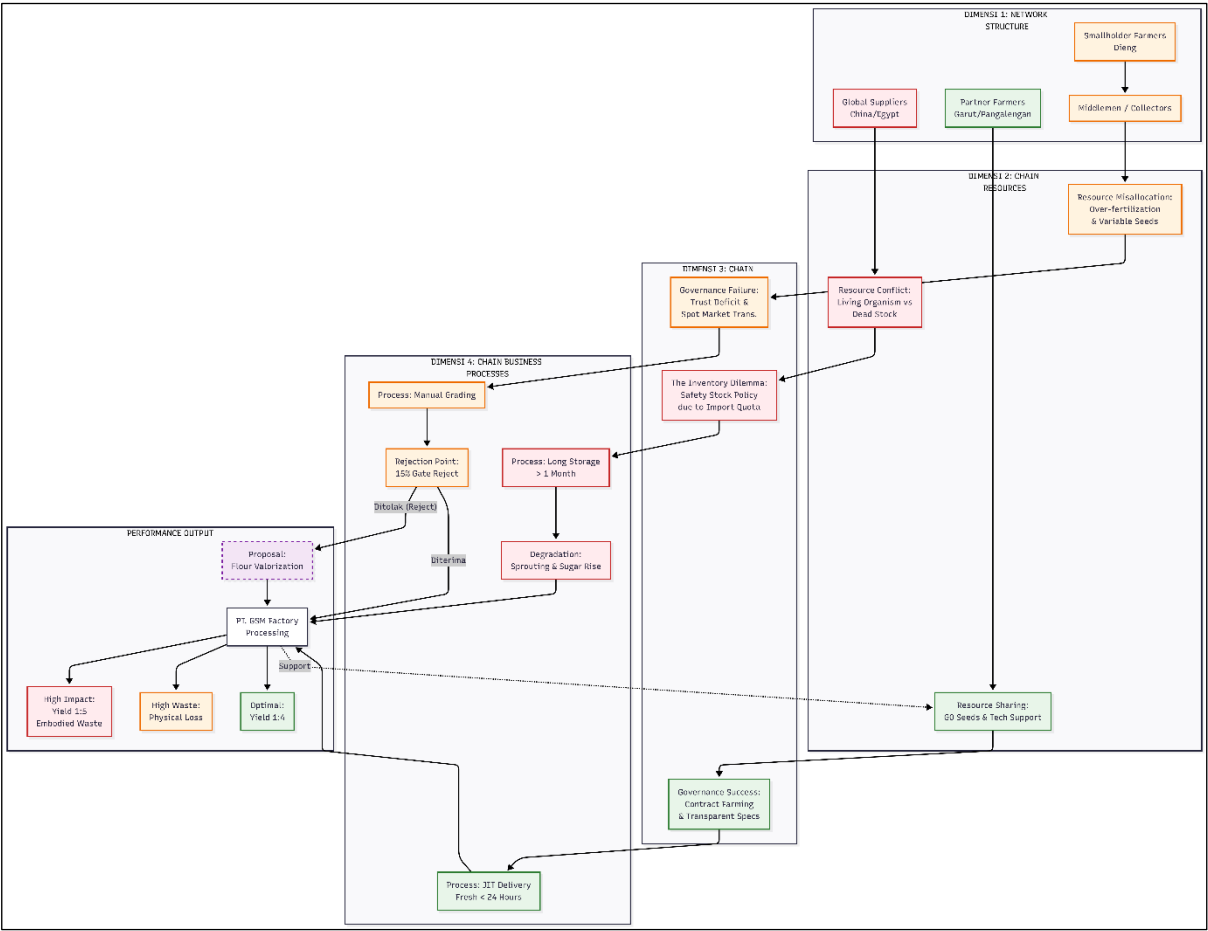


Figure 3: Rich picture of situational analysis based on the FSCN framework.
Source: Authors, (2026).

III.1.1 The Structural Disconnect: Trust Deficits and Market Failures (Dieng Cluster)

In the Dieng Plateau cluster, the primary barrier to efficiency is fundamentally rooted in a flawed Network Structure. Based on the Structure-Conduct-Performance paradigm, the market configuration exhibits oligopsonistic characteristics, where the bargaining power of independent smallholders is structurally suppressed by a dense layer of intermediaries [20]. In FSCN terminology, this represents a

"fragmented network" characterized by severe information asymmetry, where critical market signals—specifically industrial quality specifications—fail to transmit upstream to producers. This structural disconnect is exacerbated by a critical failure in Chain Management, specifically within the behavioral domain. Informant E-2, a tissue culture specialist and local community leader, identified that past failures in contract farming schemes have engendered a deep-seated "Trust Deficit." He noted that "villagers often view corporate entry with suspicion, perceiving it as a threat of exploitation rather than an economic partnership" [23]. This psychosocial barrier acts as a transaction cost that prevents the establishment of formal governance mechanisms. Consequently, farmers are forced to rely on traditional spot markets [37], that give precedence to immediate cash payments over quality incentives. The absence of coordinated Chain Management leads to the neglect of post-harvest handling protocols. Validating this diagnosis, Informant E-3 (National Seed Assessor) confirmed that this governance failure results in a rejection rate of 15% at the industrial gate, primarily due to non-compliant Specific Gravity parameters. Without repairing the relational capital (trust) required for effective network governance, technological interventions alone remain insufficient to restore the flow of materials to the industry.

III.1.2 Technical Inefficiency and Input Intensity (Upstream Reality)

At the cultivation level, the structural disconnects manifest as a severe misallocation of Chain Resources. A comparative analysis between the "Scientific Benchmark" in Pangalengan and the independent smallholder systems in Dieng and Batu demonstrates a considerable Yield Gap, driven by the disparity in intangible resources (knowledge and skills). While Informant E-1 (Senior Agronomist) achieves productivity levels of 45 tons/ha through precision Standard Operating Procedures (SOPs), the average small-holder yield stagnates at 18–20 tons/ha [38]. Ironically, farmers respond to this low productivity with irrational input intensification. Empirical studies in Dieng demonstrated massive over-fertilization behavior, where N-P-K application rates far exceed recommended doses without yielding significant production gains [19]. According to Informant E-1, this behavior is driven by a "follower mentality" and a lack of independent research among farmers, trapping them in a cycle of high costs and soil degradation. This inefficiency is also quantitatively confirmed in the Batu cluster. Using Data Envelopment Analysis (DEA), [21] found that 58.3% of farmers in Sumber Brantas operate below technical efficiency (efficiency score < 1), primarily due to operating at an increasing return to scale (IRS). In the context of Life Cycle Assessment (LCA), these findings indicate that every kilogram of potatoes from independent smallholders carries a significantly higher environmental load (embodied footprint)—due to fertilizer and land waste—compared to the efficient corporate farming model.

III.1.3 Vulnerability in Integrated Clusters (Batu Cluster)

Contrary to the conventional assumption that geographical proximity guarantees network efficiency, the industrial cluster in Batu (East Java) exhibits an "Integrated but Fragile" characteristic. While the Network Structure appears spatially compact with short logistical routes (< 15 km), the Chain Business Processes are plagued by severe discontinuity. Ideally, a short supply chain should facilitate responsiveness (Agility) and minimize waste. However, the local Small and Medium Enterprise (SME) processing industry faces high operational risks due to the unreliability of material flow. Based on Fuzzy Failure Mode and Effect Analysis (F-FMEA), "Raw Material Discontinuity" was identified as the second-highest priority risk facing the local industry, surpassing even capital constraints [22]. This supply uncertainty forces the industry to frequently halt production or, more detrimentally, to accept sub-standard raw materials to keep the lines running. This disruption effectively breaks the continuous Chain Business Process required for industrial efficiency. This operational volatility ultimately escalates the Cost of Goods Manufactured (COGM). As emphasized by Informant E-5 (Industrial Loss Analysis Expert), the variability in local raw material quality directly impacts the "material loss" metrics in the factory, rendering local products less price-competitive against consistent imports. The Batu case study empirically proves that spatial integration (Network Structure) does not equate to supply chain resilience without the presence of robust coordination mechanisms (Chain Management). These three findings—the trust deficit in Dieng, chemical input inefficiency, and supply fragility in Batu—constitute a "Systemic Lock-in." Large industries are compelled to import starch (up to 3 tons/day per factory, per Informant E-4) not due to a lack of harvest, but due to the domestic supply chain's systemic failure to guarantee quality and consistency. Therefore, the solution proposed in this study (Flour Valorization Scenario) serves not merely as a technological alternative but as a decoupling strategy to break the reliance on this inefficient fresh supply chain.

III.1.4 The Industrial Paradox: Inventory Dilemma in Large-Scale Manufacturing

Finally, the diagnosis reveals a critical and often overlooked inefficiency within the large-scale industrial cluster, representing a paradox in Chain Management. While the SME cluster struggles with scarcity, large-scale multinational manufacturers face a diametrically opposed vulnerability: the "Inventory Dilemma." Informant E-6 (Supply Chain Manager) revealed a crucial insight: to mitigate the external risks of import quota regulations and volatile Fast-Moving Consumer Goods (FMCG) demand, industrial actors adopt a "buffering strategy" by maintaining excessive safety stocks. From an FSCN perspective, this represents a fundamental misalignment between Chain Management decisions (inventory planning policies) and Chain Resources characteristics (product biology). Informant E-6 emphasized that potato tubers are physiologically active organisms ("living resources") that continue to respire and degrade post-harvest. Therefore, the prolonged storage necessitated by regulatory friction inevitably triggers physiological deterioration—specifically sprouting and the accumulation of reducing sugars (glucose/sucrose). This biological degradation creates a scenario where the Chain Business Process of storage itself becomes a primary source of waste. Informant E-6 confirmed that for fresh tubers (<1 month), the conversion ratio is optimal at 1:4.

However, for "buffered" stocks (>1 month), this ratio deteriorates to 1:5 due to rejection caused by the Maillard reaction (browning) during frying. This finding uncovers a "hidden" environmental cost: the modern supply chain incurs significant physical losses not due to a lack of processing technology, but due to the inherent perishability of the inventory buffer itself. This "Systemic Lock-in"—comprising trust deficits in Dieng, resource misallocation upstream, process fragility in Batu, and inventory paradoxes in the industry—forms the baseline inefficiency that drives the environmental burdens quantified in the subsequent Life Cycle Assessment (LCA).

III.2 MEASURING IMPACT: LIFE CYCLE ASSESSMENT

The LCA results substantiate the FSCN-based situational analysis by demonstrating that environmental performance is not solely determined by processing technology, but by the systemic conditions under which that technology operates. As revealed by the three evaluated streams, technological modernization does not guarantee emission reductions when supply chain governance and inventory management remain misaligned. While the optimal industrial configuration (Stream A-1) achieves the lowest global warming potential, this benefit is contingent upon fluid material flows and synchronized post-harvest handling. Under conditions of regulatory uncertainty and inventory buffering (Stream A-2), the same industrial system exhibits a higher carbon footprint than the traditional SME baseline. This finding empirically confirms the structural argument advanced in the situational analysis: inefficiencies embedded in chain management and storage practices can offset, or even reverse, the environmental gains expected from technological upgrading.

III.2.1 Life Cycle Impact Assessment (LCIA)

The Global Warming Potential (GWP 100a) results reveal a non-linear relationship between technological modernization and environmental performance (Figure 4). The traditional SME stream (Stream B) generates 2,500.80 kg CO₂ eq per functional unit. Despite utilizing less efficient thermal energy sources (LPG), the absence of cold storage and shorter logistical distances keeps the total emission footprint moderate. Under ideal conditions, the industrial stream (Stream A-1) achieves the lowest impact at 2,429.10 kg CO₂ eq, representing a 2.8% reduction compared to the baseline. This confirms that economies of scale and continuous processing technologies can offer environmental benefits when supply chains are fluid. However, Stream A-2 under conditions of regulatory uncertainty and market demand fluctuation (Inventory Paradox), the industrial footprint surges to 2,659.99 kg CO₂ eq. This represents a 6.4% increase over the traditional baseline, effectively negating the technological advantages of modernization.

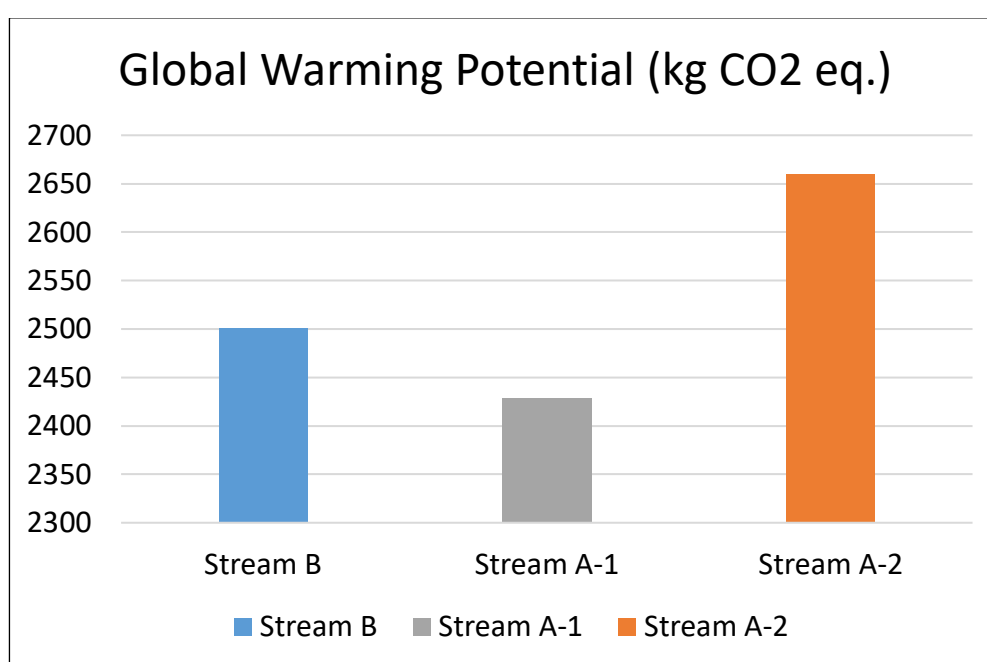


Figure 4: Global warming potential comparison across three supply chain scenarios.
Source: Authors, (2026).

The Sankey diagrams in Figure 5 provide a structural visualization of the 'Inventory Paradox,' revealing that the environmental penalty is driven not only by direct energy consumption but significantly by material inefficiency. In the Optimal Scenario (Stream A-1) diagram [A], the system exhibits a relatively balanced distribution of environmental burdens. The dominant hotspot is the upstream production of Palm Kernel Oil (1.866×10^3 kg CO₂ eq), which is intrinsic to the deep-frying process. The contribution from Industrial Storage (Proses_07) is visible as a distinct tributary contributing 3.011×10^2 kg CO₂ eq (approximately 12.4% of the total impact). This represents the 'baseline cost' of modern logistics under functional conditions. The Paradox Scenario (Stream A-2) diagram [B] demonstrates a dramatic structural shift. While the final output remains the same (1,000 kg of chips), the upstream burdens expand significantly due to the Double Penalty mechanism. The most striking feature in Diagram B is the thickening of the Palm Kernel Oil flow, which surges to 2.333×10^3 kg CO₂ eq. This visual expansion confirms the 'Material Penalty' hypothesis: the input inefficiency (increasing oil usage from 400 kg to 500 kg to accommodate the higher potato input of 5,000 kg) forces the system to carry a heavier embodied carbon load. The system is essentially 'processing waste,' consuming high-carbon ingredients (oil) on tubers that will eventually be rejected.

The total downstream impact swells from 2.429×10^3 in Scenario A to 2.660×10^3 kg CO₂ eq in Scenario B. This visual evidence refutes the notion that supply chain disruptions are merely logistical issues; Figure 5 clearly classifies them as resource efficiency disasters, where the environmental cost of wasted inputs (oil and raw materials) compounds with the energy cost of prolonged storage.

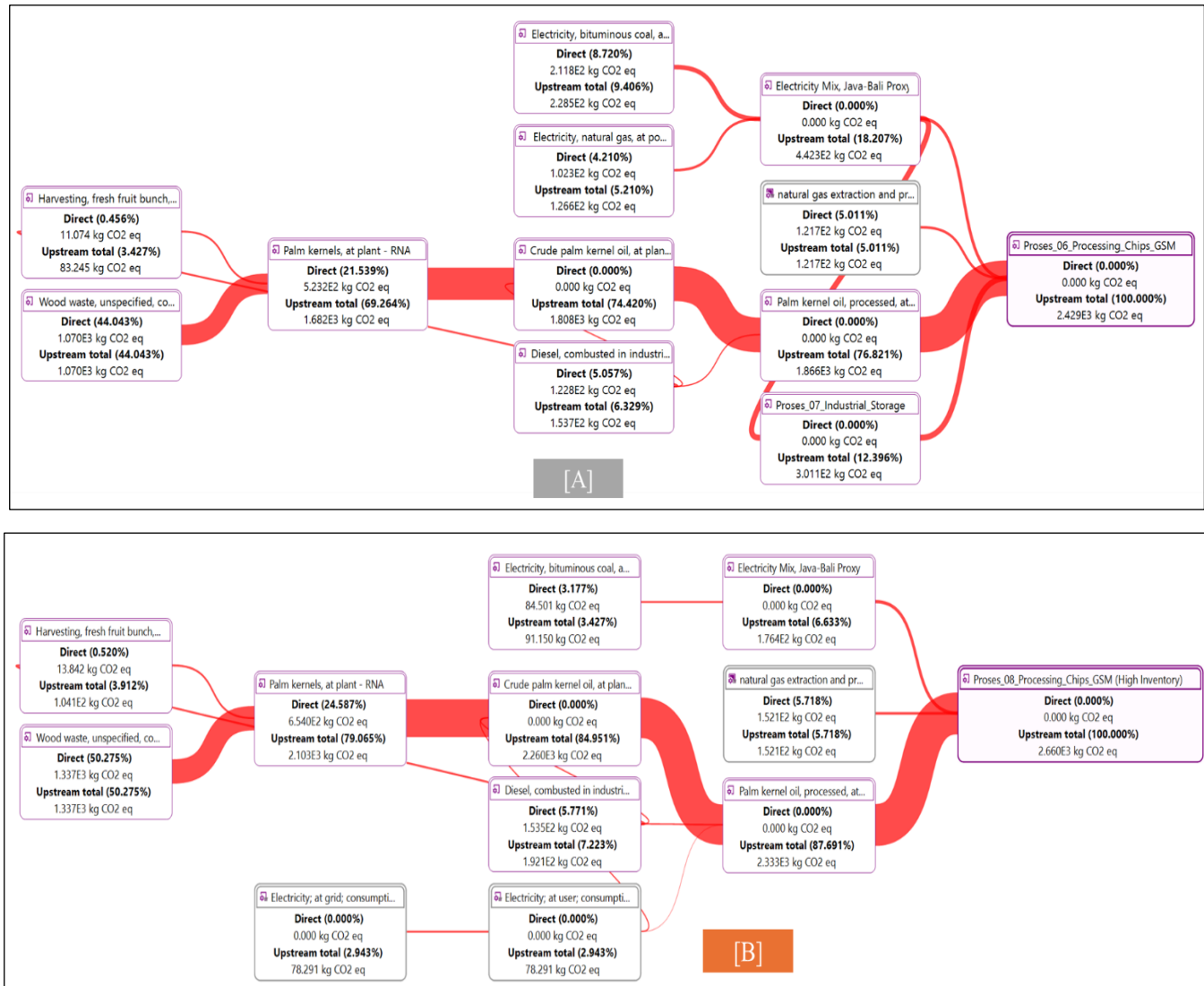


Figure 5: Comparative Sankey Diagrams of GWP 100a flows [A] Stream A-1 (Optimal) Shows a streamlined emission flow where industrial storage contributes moderately (~12.4%) to the total burden; [B] Stream A-2 (Paradox) visualizes the "Swelling Effect" caused by supply chain inefficiencies. Note the significant expansion in the Palm Kernel Oil flow, representing the embodied carbon of wasted materials mandated by the lower yield ratio.

Source: Authors, (2026).

III.3 THE ENVIRONMENTAL COST OF SUPPLY CHAIN INEFFICIENCIES

The LCA results indicating an emission surge in Stream A-2 align with the concept of "Material Penalty" within the Food Loss and Waste (FLW) literature. A systematic review emphasizes that downstream food waste (manufacturing stage) carries a "double burden" as it embodies the accumulated emissions from all upstream activities [2]. Expert interviews with R&D specialists validate this mechanism [9], [39]. In an ideal continuous frying system, industrial waste should remain below 2%. However, when raw materials degrade due to prolonged storage caused by import quota restrictions, the waste rate spikes. The LCA simulation captures this by reflecting an increase in frying oil consumption (from 400 kg to 500 kg) to process chips that are ultimately rejected. Consequently, the industry is not merely discarding potatoes; it is wasting high-carbon-footprint palm oil, thereby amplifying the environmental impact.

III.3.1 Upstream Environmental Trade-Offs Beyond the Gate-to-Gate Boundary in Stream B

While Stream B appears superior in Gate-to-Gate emission metrics (2,500 kg CO₂ eq), the literature warns against romanticizing the traditional system. The "Fresh-to-Fry" efficiency is partial and fails to account for severe ecological externalities at the cultivation stage (Cradle). Studies in the Dieng Plateau demonstrate that intensive potato farming practices employed by Stream B farmers have led to massive soil erosion and sedimentation, negatively impacting local tourism and water bodies [40], [41]. Previous studies found that the use of production inputs (fertilizers/pesticides) by farmers in Dieng is characterized by decreasing returns to scale, indicating excessive chemical usage that degrades soil health [19]. Thus, the low-carbon profile of Stream B's manufacturing phase is offset by long-term ecological degradation in the upstream phase, posing a threat to the supply sustainability itself [42].

III.3.2 Structural Barriers: Oligopsony and Risk Asymmetry

Why does Stream A fail to absorb local produce from Stream B to mitigate import dependency? The analysis points to a fundamental market failure. Earlier research in Batu and Wonosobo confirms that the local potato market structure tends towards oligopsony [20], [43]. Farmers lack bargaining power against intermediaries. This is corroborated by Informant E-2, who noted that pricing is often determined by subjective visual negotiation rather than objective metrics like specific gravity or starch content [23]. Thus, farmers are risk-averse to cultivating the Atlantic variety required by Stream A. If rejected by the industry, there is no alternative market. Conversely, the Granola (vegetable) variety has a liquid market in traditional sectors. This risk asymmetry—as detailed in the risk analysis [44]—perpetuates the "structural wall" separating the two streams.

III.4 CIRCULAR SOLUTIONS: BRIDGING THE GAP

The findings of this study suggest a critical need to shift from "linear efficiency" (which fails under uncertainty) to "systemic circularity." Drawing on the framework by [2], the substantial material losses identified in this study—specifically in some clusters, reaching up to 70% off-grade tubers in Stream B and the starch-rich wastewater in Stream A—represent a "misplaced resource" rather than mere waste.

III.4.1 Technical Feasibility for Smallholders: From Waste to Starch/Flour

The primary barrier to integrating Stream B (Local) into the industrial supply chain has been quality mismatch (high sugar, small size). However, literature confirms that off-grade potatoes are technically viable for processing into Potato Flour and Native Starch, technologies that are accessible to smallholder intermediaries. Whole potato flour produced from small or irregular tubers retains significantly higher nutritional value (fiber and protein) compared to refined starch and can be processed using simple drying technologies (drum or cabinet dryers) suitable for SME scales [44]. Furthermore, potato peel waste and trimmings—abundant in the "Pasar BS" market described by Informant E-3—contain high levels of phenolic compounds and can be upcycled into functional food ingredients [45]. For starch extraction, while pharmaceutical-grade starch requires sophisticated refining, native starch production relies on mechanical rasping and sedimentation principles that can be decentralized [46]. By [47] further argue that decentralized processing hubs in developing countries significantly reduce post-harvest losses by converting perishable tubers into stable powder forms near the farm gate. This validates the potential of an "Intermediate Hub" in Dieng or Pangalengan to absorb the 70% loss reported in the situational analysis, converting it into a commodity with a shelf-life of 1–2 years, thereby decoupling the product from the volatility of fresh-market prices [48].

III.4.2 Theoretical Critique: The Failure of Linear FSCN

The existence of the "Inventory Paradox" exposes the limitation of the standard Food Supply Chain Network (FSCN) framework [26], which is premised on the assumption of linear flow and information transparency. By [49] critique such linear models for treating waste as an "external endpoint" to be minimized, rather than an "internal flow" to be managed. In the context of the Indonesian potato industry, the linear FSCN model fails to account for "Systemic Lock-ins," in which oligopsonistic market structures prevent the flow of goods from smallholders to modern industries [50]. The standard model assumes that if demand exists (Stream A imports), supply (Stream B) will naturally adjust. However, our findings show that risk asymmetry (price volatility vs. quality strictness) prevents this adjustment. Therefore, a new theoretical lens is required—one that integrates Circular Economy (CE) principles directly into supply chain configuration [51].

III.4.3 Research Novelty: The Integrated Circular FSCN Model

Synthesizing the empirical data with the circular economy literature, this study proposes a novel framework: the Integrated Circular FSCN. Unlike the traditional FSCN, which focuses on vertical integration (Farm to Factory), this model introduces a "Horizontal Valorization Loop" via an Intermediate Valorization Hub. The decoupling mechanism works by converting the 70% off-grade tubers from Stream B into potato flour/starch. The Hub decouples the farmer from the risks of the fresh market (price fluctuation and rotting). This addresses the "vulnerability" identified in the Livelihood analysis. The output (starch/flour) serves as an input for the Fabricated Snack Industry (a subset of Stream A), substituting imported starch. This creates a "Back-Loop" that standard FSCN models lack. As argued by [52], circular food systems increase resilience by diversifying input sources. This model solves the Inventory Paradox by reducing the industry's absolute reliance on imported raw tubers, as a portion of demand is met through stable, locally sourced starch/flour. In this case, the Integrated Circular FSCN resolves the "Structural Bifurcation" not by forcing smallholders to grow industrial potatoes (which is risky), but by industrializing the smallholder's waste stream.

This shifts the paradigm from "Managing Quality Constraints" to "Managing Resource Valorization," creating an avenue to reduce the sector's GWP from the paradoxical 2,659 kg CO₂ eq back towards sustainable levels. The Integrated Circular FSCN model (Figure 6) serves as a structural remedy to the 'Inventory Paradox' by transforming the systemic disconnect between local production and global sourcing into a synergistic loop. By strategically positioning an Intermediate Valorization Hub to upcycle the 70% off-grade tubers from the local stream into industrial-grade starch, the model effectively decouples the agro-industry from its absolute reliance on volatile import quotas. This architectural redesign shifts the paradigm from a vulnerable linear system—prone to the 'Material and Energy Penalties' identified in the LCA—toward a resilient circular network, demonstrating that true decarbonization in tropical supply chains requires not merely technological optimization, but the strategic valorization of 'misplaced resources' to bridge the gap between smallholder realities and industrial demands.

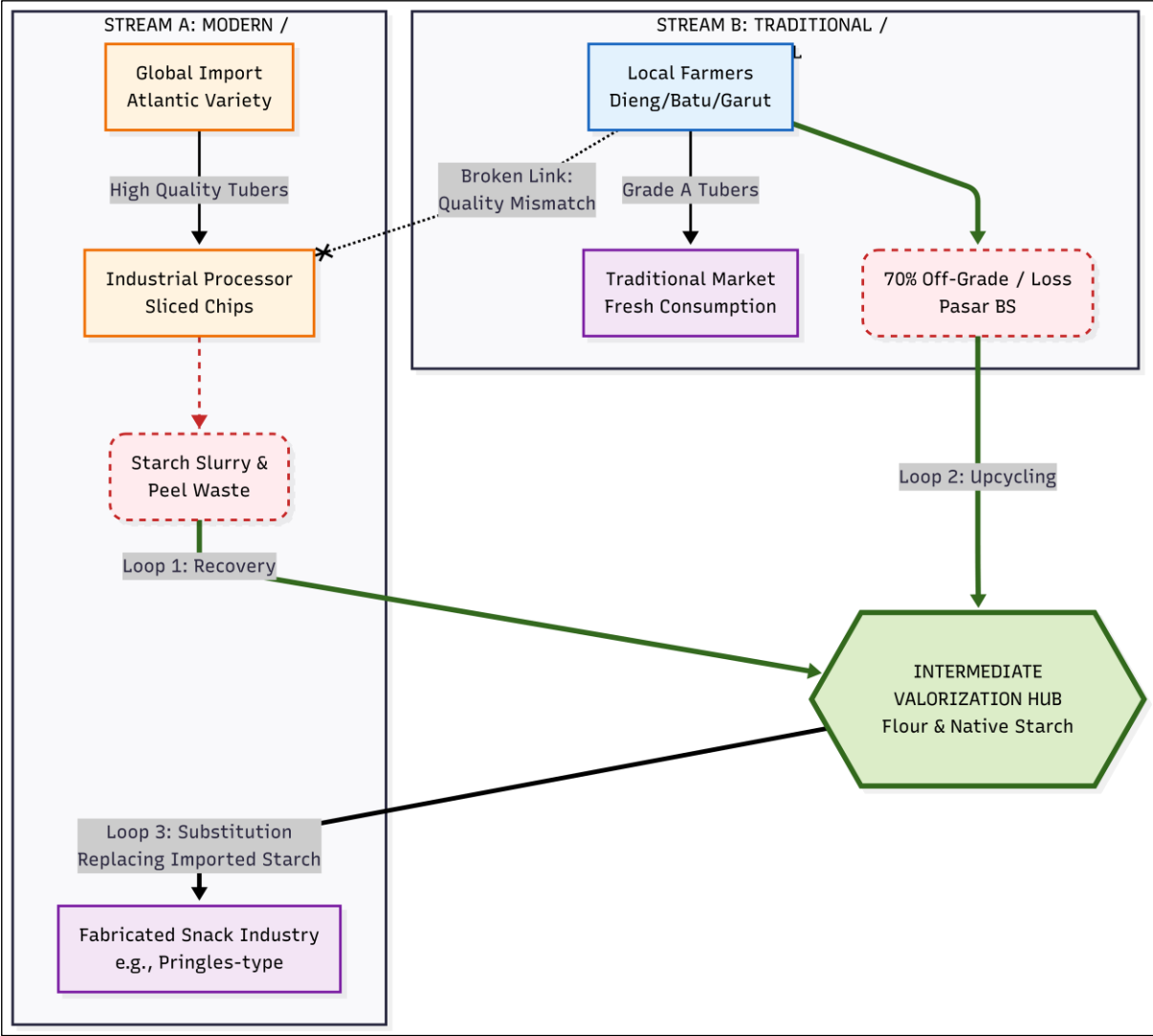


Figure 6: The Integrated Circular FSCN model for the Indonesian potato agro-industry.
Source: Authors, (2026).

IV. CONCLUSIONS

The findings of this study show that environmental performance in agro-industrial supply chains cannot be inferred from processing technology alone. In the Indonesian potato sector, industrial systems achieve lower emissions only when material flows are stable and storage durations are short. Under regulatory pressure and demand uncertainty, inventory buffering becomes a dominant driver of inefficiency. The resulting combination of prolonged cold storage and quality deterioration increases both energy use and material requirements, leading to a higher carbon footprint than that of smaller-scale, low-technology supply chains. This outcome illustrates what is referred to in this paper as the Inventory Paradox: practices intended to protect operational continuity instead amplify environmental burden when biological constraints are ignored. The Integrated Circular FSCN proposed in this study should be interpreted as a structural design response to this paradox rather than a validated solution. By redirecting off-grade local tubers into intermediate valorisation pathways, the framework conceptually reduces dependence on volatile fresh-tuber imports and limits the need for excessive inventory buffering. Its value lies in clarifying how circularity can be embedded at the network level, rather than in providing immediate performance claims. Future research is required to translate this design into an operational model and to test its effectiveness under different market and policy conditions using system dynamics and scenario-based simulation.

V. AUTHOR'S CONTRIBUTION

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Methodology: Adrin Ramdana Rauf, Marimin Marimin, Popong Nurhayati and Suprehatin Suprehatin.
Investigation: Adrin Ramdana Rauf.
Discussion of results: Adrin Ramdana Rauf, Marimin Marimin.
Writing – Original Draft: Adrin Ramdana Rauf.
Writing – Review and Editing: Adrin Ramdana Rauf, Marimin Marimin, Popong Nurhayati and Suprehatin Suprehatin.
Resources: Adrin Ramdana Rauf.
Supervision: Marimin Marimin, Popong Nurhayati and Suprehatin Suprehatin.
Approval of the final text: Marimin Marimin, Popong Nurhayati and Suprehatin Suprehatin.

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