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Socio-Technical Transformation of Indonesia's National Food System: An Integrated Approach Based on Circular Supply Chain Management, Human Factors, and Agent-Based Modeling

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Received: 10-04-2025 **Revised:** 12-29-2025 **Accepted:** 01-21-2026

Citation: Purnomo, H., Aminuddin A. P., R. A., Immawan, T., & Firdaus, F. (2026). Socio-technical transformation of Indonesia's national food system: An integrated approach based on circular supply chain management, human factors, and agent-based modeling. *Chall. Sustain.*, *14*(1), 157–168. https://doi.org/10.56578/cis140110.

Abstract: This study proposed a socio-technical model to transform the national food system in Indonesia toward greater inclusiveness and sustainability. By integrating circular supply chain management (CSCM), macro-ergonomics, and human factors, the research examined how interactions among key stakeholders such as farmers, micro, small, and medium enterprises (MSMEs), consumers, and government shaped sustainability and equity outcomes. A mixed-methods approach combining thematic analysis (TA), social network analysis (SNA), and agent-based modelling (ABM) was employed to identify structural bottlenecks and leverage points for systemic change. Qualitative insights informed network structures and behavioral rules within the simulation model. The results indicated that MSMEs and consumers exerted strong systemic influence on behavioral change and redistribution potential despite their peripheral network positions, while government actors, though structurally powerful, exhibited limited embeddedness in day-to-day interactions. Simulation scenarios demonstrated that integrated interventions combining policy enforcement, education, and technology incentives yielded the greatest improvements, including reductions in food loss and waste (FLW), greater equity, and improved sustainability performance. The proposed interdisciplinary framework provides actionable guidance for policy design and system reconfiguration in emerging economies which are facing challenges from the complex food system.

Keywords: Circular supply chain; Socio-technical; Sustainable food systems; Macro-ergonomics; Social network analysis; Agent-based modelling

1. Introduction

The global food system is undergoing unprecedented stress due to a confluence of environmental, social, economic, and technological challenges. Climate change is disrupting agricultural cycles, reducing yields, and exacerbating food insecurity (El Bilali et al., 2021). Simultaneously, the global population is projected to reach nearly 10 billion by 2050, thus intensifying the demand for food while increasing pressure on already-depleted natural resources (Purnomo et al., 2024). The sustainability of food systems was further compromised by social inequality, fragile governance, urban sprawl, and the exponential growth of global food waste estimated to be over 1.3 billion tons per year (Bonilla Cedrez et al., 2023). Moreover, the dominant linear model of food production and consumption, characterized by the "take-make-dispose" pattern, has proven inefficient and environmentally destructive to call for a paradigm shift toward circularity and inclusiveness (da Silva Duarte et al., 2021).

In the context of Indonesia, the situation is both unique and urgent. As an archipelagic nation with one of the world's largest agricultural populations and food markets, Indonesia faces a paradox: while rich in biodiversity and food-producing regions, it grapples with rising food insecurity, post-harvest losses, fragmented supply chains, and unequal access to markets and technologies (Syahlani et al., 2024). Integrated, adaptive, and inclusive supply chain governance has not yet kept pace with the rapid urbanization and digitalization of food services (e.g., food delivery platforms). Furthermore, Indonesia has some of the highest rates of food loss and waste (FLW) in Southeast Asia, contributing to both nutritional deficiencies and environmental degradation. These issues are compounded by the marginalization of smallholder farmers and informal food actors, weak institutional coordination, and a lack of systemic approaches that combine infrastructure, policy, and behavior change.

Against this backdrop, this study argued for the socio-technical transformation of Indonesia's national food system through the integration of circular supply chain management (CSCM), macro-ergonomic principles, and human-centered design. The socio-technical perspective recognizes that food systems are not only shaped by technologies and institutions but also by the dynamic interactions among human actors, organizational structures, cultural norms, and environmental constraints. Through embedding macro-ergonomics and human factors into CSCM, this study aims to ensure that transitions of the food system are not only ecologically sustainable and economically viable but also socially just and participatory.

1.1 Problem Statement and Aim of the Research

The necessity of this research stems from a lack of holistic and interdisciplinary models that address the technical and social complexities of Indonesia's food system. Existing policy frameworks often focus on isolated interventions such as agricultural subsidies and digitalization, without addressing systemic inefficiencies or empowering key actors including farmers, micro, small, and medium enterprises (MSMEs), and consumers. Furthermore, few studies to date have operationalized socio-technical models with computational tools such as social network analysis (SNA) and agent-based modeling (ABM) to simulate policy scenarios and behavioral feedback loops within the food system.

This study therefore seeks to fill these gaps by pursuing the following research objectives:

(1) To map and analyze the structural dynamics of the Indonesian food system using SNA, in order to identify key actors, bottlenecks, and leverage points.

(2) To employ ABM to develop a scenario-based simulation model that accurately depicts the behavioral, institutional, and environmental dynamics of a circular food supply chain.

(3) To create a comprehensive framework that integrates CSCM, macro-ergonomics, and human factors to improve the inclusivity, sustainability, and resilience of the national food system.

The novelty of this research lies in its interdisciplinary integration of CSCM, ergonomics, and behavioral systems modeling. This approach remains largely underexplored in the literature on food systems, particularly within Southeast Asia. By coupling qualitative thematic insights with quantitative network and agent-based simulations, the study offered both diagnostic and predictive capabilities for food system reform. Furthermore, having emphasized inclusivity and socio-technical fit, the model has practical relevance for policy innovation, stakeholder engagement, and regional adaptation, thus offering a potentially scalable blueprint for other developing countries facing similar challenges in the food system.

2. Methodological Approach

To address the multidimensional and socio-technical nature of the national food system in Indonesia, this study employed an integrative methodological framework that combined qualitative thematic analysis (TA), social network mapping, and simulation-based modeling. The approach was designed to ensure both depth of understanding and system-level insight across three core dimensions, i.e., structure, behavior, and interaction.

The methodology unfolded in four key phases:

(1) TA—to extract emergent issues, perceptions, and contextual themes from stakeholders.

(2) SNA—to map and measure the structural properties and relational dynamics of the food system.

(3) ABM—to simulate policy and behavioral scenarios in a virtual system representing real-world complexities.

The integration of the framework aligned the findings with CSCM, macro-ergonomics, and principles of human factors, resulting in a practical model ready for application.

2.1 Thematic Analysis

TA was conducted to identify key socio-technical challenges and behavioral patterns from qualitative data. The data were collected from semi-structured interviews, document analysis, and field observations involving multiple stakeholders in the food system (e.g., farmers, MSMEs, government officials, non-governmental organizations (NGOs), and consumers).

The corpus of the qualitative data consisted of 32 semi-structured interviews involving key stakeholder groups: smallholder farmers (10); MSMEs in food processing and distribution (8); government officials at local and national levels (6); NGO representatives (4); and consumers (4). Data collection was conducted between March and August 2024 across three regions representing western, central, and eastern Indonesia (Java, Sulawesi, and Sumatra). Information from policy documents, institutional reports, and field observations complemented interview records.

All interviews were transcribed verbatim and analyzed via a six-step thematic coding procedure following Braun and Clarke (Ahmad et al., 2024). Initial open coding was conducted independently by two researchers to identify salient concepts. Codes were then iteratively refined, clustered into higher-order themes, and reviewed through expert validation to ensure consistency, credibility, and analytical rigor.

Based on Table 1 the emerging themes are:

(1) Limited access to circular technology and infrastructure;
(2) Weak consumer awareness of food sustainability;
(3) Marginalization of smallholders and MSMEs;
(4) Incoherent and fragmented regulatory framework; and
(5) Cultural norms leading to food overconsumption and waste.

Table 1. Analytical procedures

Step	Description	Application in the Study
1. Familiarization	Immersing in raw data (e.g., transcripts, notes, and documents)	Interview with farmers, consumers, and micro, small, and medium enterprises (MSMEs)
2. Initial Coding	Labeling important features in the data	e.g., “low access to tech”, “food waste”, and “policy gaps”
3. Theme Development	Grouping codes into coherent patterns	e.g., “technology access”, “regulatory weakness”, and “cultural behavior”
4. Theme Review	Cross-checking against raw data for consistency	Iterative refinement with expert validation
5. Theme Definition	Naming and finalizing themes	e.g., “circular infrastructure deficit”
6. Analytical Narrative	Integrating themes into system diagnosis	Used to inform agent-based modelling (ABM) parameters and social network analysis (SNA) node properties

2.2 Social Network Analysis

SNA was employed to examine the structure of relationships among actors in the national food system. This approach helped identify power asymmetries, communication bottlenecks, and collaborative potential within the network.

SNA Steps (Huang et al., 2023; Trach et al., 2023):

(1) Node Identification: Key stakeholders were identified as nodes (e.g., farmers, MSMEs, government agencies, NGOs, consumers, etc.).
(2) Edge Definition: Connections were defined based on collaboration, information flow, or exchange of resource (e.g., subsidies, supply links, training programs, etc.).
(3) Adjacency Matrix Construction: Binary and weighted matrices were developed to reflect the interaction of strength.
(4) Metric Calculation: Metrics such as degree, betweenness, closeness, and eigenvector centrality were computed using Gephi.
(5) Network Visualization: The structure was visualized to highlight central actors and clusters.
(6) Interpretation: Insights were drawn to inform the points of intervention.

The roles and interpretive value of each network metric used in this study are presented in Table 2, providing a conceptual basis for understanding actor influence and network positioning.

Table 2. Key metrics and their roles

Metric	Description	Insight
Degree Centrality	Number of direct connections	Influence on distribution
Betweenness Centrality	Role in connecting clusters	Strategic bridging capacity
Closeness Centrality	Speed of access to others	Dissemination of information
Eigenvector Centrality	Influence based on powerful neighbors	Potential of Systemic impact

2.3 Agent-Based Modeling

ABM was used to simulate the evolution of individual decisions and interactions among food system actors under different policy and behavioral scenarios.

ABM Development Process (Aftabi et al., 2025; Guo et al., 2022):

(1) Definition of Agents: Stakeholders were modeled as heterogeneous agents with individual rules, preferences, and decision heuristics (e.g., smallholder farmers, MSMEs, consumers, government, NGOs, and tech providers).
(2) Environment Modeling: Simulated environment included markets, resources like water and land, the availability of technology, policy signals, and socio-cultural factors.
(3) Behavioral Rules:
- Farmers choose production methods based on cost, training, and incentive signals.
- MSMEs adopt or reject circular practices based on consumer demand and access to technology.
- Consumers make decisions influenced by price, education, and social norms.
- NGOs target areas of vulnerability to implement redistributive action.
- Government's agents update policies based on systemic feedback.

Scenario Simulation
- S1: Status quo (linear system and no policy change)
- S2: Technology subsidy and investment
- S3: Regulatory enforcement on food waste
- S4: Education and awareness campaigns
- S5: Integrated intervention (subsidy + regulation + education)

Outcome Variables
- Percentage of FLW
- Percentage of circular practices adopted
- Equity of food distribution
- Economic and environmental performance
- Agent satisfaction and inclusion level

2.4 Integration with CSCM, Ergonomics, and Human Factors

All stages of analysis were aligned with CSCM principles and ergonomics frameworks:
- CSCM: The goal is to design looping flows that encompass production, distribution, consumption, and end-of-life processes, such as composting and food banks.
- Macro-ergonomics: To assess organizational structures, stakeholder participation, and systemic alignment.
- Human Factors: This involves incorporating decision behavior, addressing knowledge gaps, utilizing learning mechanisms, and applying user-centered design in interventions.

Each scenario of intervention was assessed not only for performance but also for fit, participation, and feasibility within local contexts.

2.5 Validity, Reliability, and Ethical Considerations

- Triangulation: Mixed-method triangulation (TA + SNA + ABM) ensured robust insights from both qualitative and quantitative data.
- Validation: SNA metrics and ABM output were reviewed by domain experts and stakeholder representatives.
- Sensitivity Analysis: Analysis was conducted in ABM to assess the robustness of outcomes to parameter variation.
- Ethics: Informed consent was obtained from all interviewees. Simulation models do not include personal data.

3. Results

This section presents the core empirical and simulated findings generated through TA, SNA, and ABM. Results were structured into a methodological stream and reported with appropriate metrics, tables, and visualizations.

3.1 Results of Thematic Analysis

A total of six major themes emerged from the qualitative analysis of interviews with stakeholders and supporting documentation. Table 3 summarizes the categories of themes, codes of representations, and frequencies.

These themes indicate systemic and multi-actor challenges that inform both the network structure and behavioral modeling.

3.2 Results of Social Network Analysis

The relational structure of the national food system was modeled by 9 types of actors (nodes) and 13 types of interactions (edges). The resulting network was sparse and modular and showed asymmetries in connectivity.

The calculated centrality scores for each stakeholder group are reported in Table 3 and Table 4, highlighting variations in influence, connectivity, and strategic positioning within the food system network.

Table 3. Thematic categories and supporting codes

Theme	Supporting Codes	Frequencies
Access to Technology and Infrastructure	"No cold chain", "Lack of processing tools", "Inconsistent logistics"	47
Consumer Literacy and Awareness	"No information on food waste", "Preference for imported goods"	39
Socio-Economic Disparities	"Low price for local produce", "Excluded from markets"	52
Regulatory Weaknesses	"No circularity incentives", "Lack of food waste policies"	31
Weak Collaboration	"No coordination with NGOs", "Disconnected from tech providers"	35
Cultural and Behavioral Patterns	"Over-ordering", "Stigma on leftover food"	28

Table 4. Centrality metrics for actors in the food system

Actor	Degree Centrality	Betweenness Centrality	Closeness Centrality	Eigenvector Centrality
Smallholder Farmers	0.500	0.125	0.300	0.2425
MSMEs (Food Sector)	0.500	0.0536	0.4375	0.4851
Government	0.500	**0.2321**	0.4500	0.2425
Consumers	0.375	0.0000	**0.5714**	**0.7276**
NGOs/Community Support Officers (CSOs)	0.375	0.2143	0.3462	0.2425
Cooperatives	0.375	0.1429	0.2812	0.2425
Tech/Logistics Providers	0.250	0.0000	0.0000	~0
Media/Educators	0.250	0.0000	0.0000	~0
Researchers	0.125	0.0000	0.0000	~0

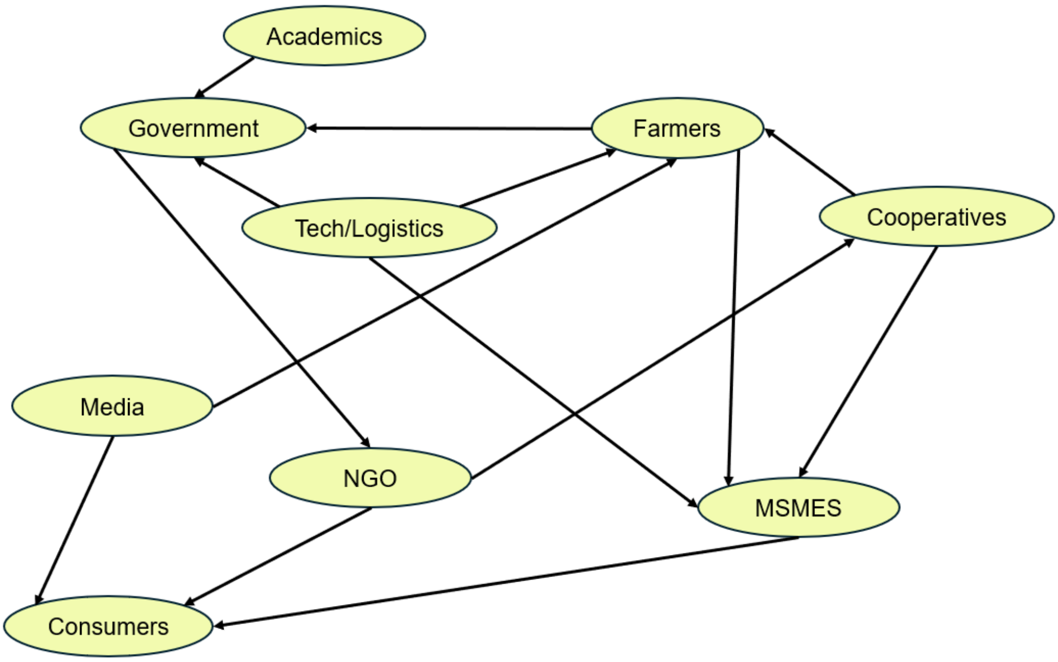

Figure 1. Social network analysis

Figure 1 displays the SNA graph to show that:

- Consumers and MSMEs are located at the network periphery, despite high eigenvector centrality.
- The government and NGOs serve as essential links between different clusters.
- Farmers and cooperatives are forming tightly knit but isolated clusters.

Each node in this SNA represents a key stakeholder in the national food system:

- The government serves as a central coordinating body that is connected to nearly all actors and reflects its

authority in policy making and regulation.
- Farmers are core producers of food and directly linked to cooperatives, NGOs, and tech/logistics.
- Cooperatives serve as intermediaries and facilitators of small-scale production, to connect farmers with MSMEs.
- MSMEs are processors, distributors, and retailers who adapt products for markets.
- Consumers are the primary force behind demand, to shape production and distribution strategies.
- NGOs facilitate capacity building and advocacy, to link grassroots actors to policy and market structures.
- Tech/Logistics providers enable the distribution, market access, and data flows across the chain.
- Media influence public awareness, consumer preferences, and political discourse.
- Academics provide research, innovation, and evidence for policy decisions.

Network Interpretation:
- The system is moderately connected, with the government, NGOs, and MSMEs serving as major hubs.
- There is no single dominant cluster, but rather overlapping spheres (e.g., production, distribution, policy, advocacy, and knowledge).
- Potential Weakness: Farmers have fewer direct ties to consumers, meaning market feedback often passes through intermediaries.
- Potential Strength: NGOs and cooperatives can act as accelerators of innovation if better integrated into policy and logistics networks.

3.3 Results of Agent-Based Modeling

A total of five policy scenarios were simulated using NetLogo over 1000-time steps and 100 replications per scenario. Key outcome variables included percentage of FLW, adoption of circular practices, and system equity. A comparative summary of simulation outcomes across all policy scenarios is provided in Table 5, illustrating differences in FLW reduction, circular adoption, equity, and stakeholder satisfaction.

Table 5. Summary of ABM simulation outcomes

Scenario	Food Loss and Waste (FLW) Reduction (%)	Adoption of Circular Practice (%)	Equity Index	Satisfaction Score
S1: Status Quo	0	8.5	0.46	0.61
S2: Technology Subsidy	18.4	26.7	0.53	0.68
S3: Regulatory Enforcement	22.1	30.1	0.58	0.65
S4: Education Campaign	27.5	34.8	0.63	0.74
S5: Combined Intervention	**45.3**	**51.2**	**0.71**	**0.82**

Additional ABM Observations:
- Behavioral imitation among consumers increased circular consumption by 17% in S4 and S5.
- Institutional feedback loops emerged in S5, where improved satisfaction led to higher policy compliance.
- Regional disparities were reduced by 32% in food access under S5.

ABM developed in this study maps the interaction flow across key stakeholders in the national food system. The simulation framework consists of interconnected agents performing distinct roles, as illustrated in the diagram.

(1) Upstream Governance and Support

The government, i.e., policy maker, acts as a central upstream agent to provide policy collaboration, subsidies/regulations, and funding programs to other agents.
- NGOs and local communities contribute to training and redistribution efforts, to directly support farmers in capacity development.
- Supporting institutions like education as well as R&D bodies supply knowledge-based inputs, thus contributing to capacity building for production and efficiency of distribution.
- Environmental factors (e.g., land, water, and market access) influence the availability of resources and act as contextual determinants of farming productivity.

(2) Production Level
- Farmers function as the primary producers within the system. Their performance is shaped by upstream interventions like government policies, NGO training, institutional capacity building, and availability of environmental resources.
- Farmers sell products to downstream actors, so as to initiate the sequence of supply chain.

(3) Midstream Distribution
- Collectors/traders aggregate products from multiple farmers and conduct bulk sales to distributors.
- Distributors manage supply distribution across various markets, to bridge the production and retail segments.

(4) Downstream Market

- Retailers serve as the final intermediaries, offering products to consumers.
- Consumer purchases generate sales data, responses, and demand signals of products; these are feedback to upstream actors, especially farmers and retailers.

(5) Feedback Loops

- The ABM structure incorporates demand-driven feedback loops to enable dynamic adaptation. Consumer demand and sales data inform production adjustments at the farmer level and policy or market adjustments at the institutional level, as illustrated in the following Figure 2.

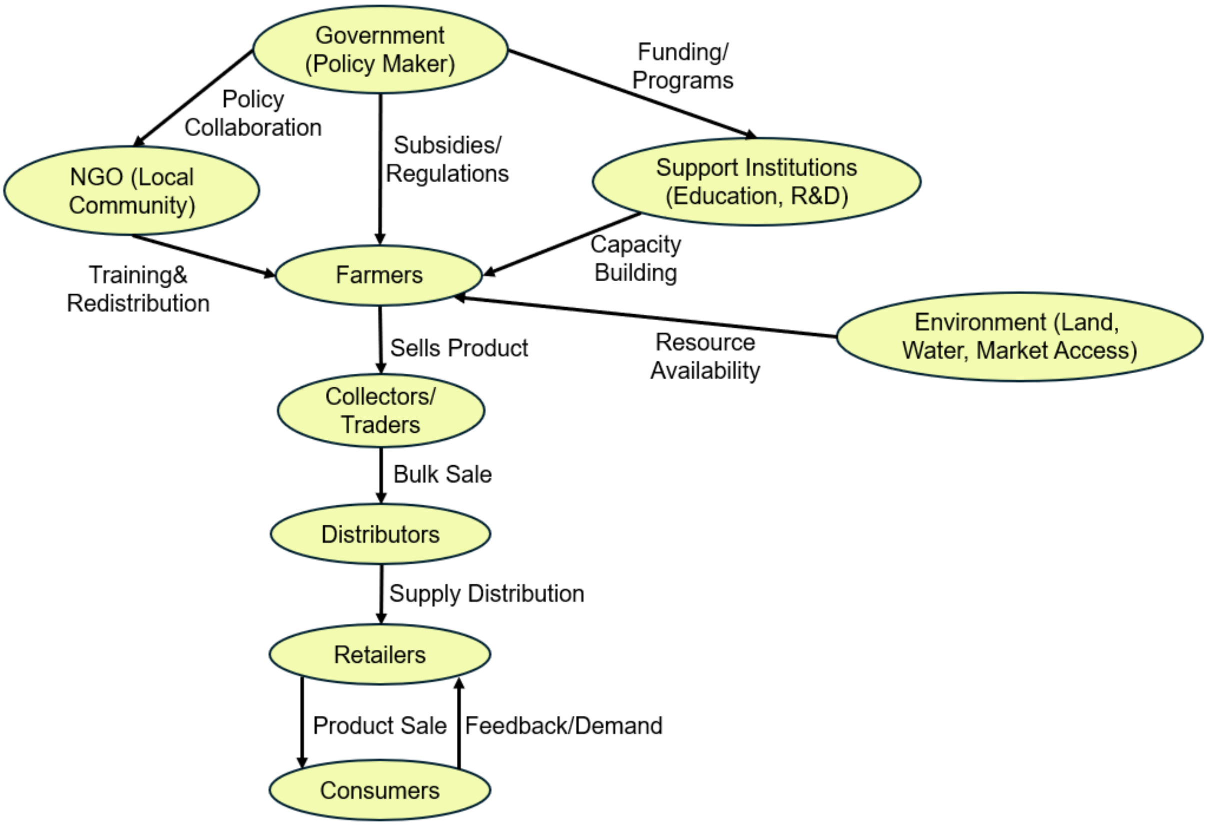

Figure 2. Agent-based modelling visual diagram

Model parameters were derived from multiple sources to enhance empirical grounding and validity. Behavioral parameters related to technology adoption, risk perception, and social imitation thresholds were informed by technical analysis of the interview data. Structural and policy-related parameters, such as the intensity of subsidy, the strength of regulatory enforcement, and coordination levels, were calibrated using secondary data and values reported in prior literature. Parameters that could not be directly observed were set in accordance with conservative assumptions and subsequently tested through sensitivity analysis.

Expert validation was conducted via iterative consultation with three domain experts from academia, government, and civil society; the professionals reviewed parameter ranges, behavioral rules, and simulation output to ensure plausibility and contextual relevance.

3.4 Causal Loop and System Insights

The causal loop diagram highlighted key feedback:

- Reinforcing loops: consumer awareness → demand for sustainable food → MSME innovation
- Balancing loops: policy enforcement → reduction in FLW → environmental gains
- Delays identified in tech adoption and training impact (average 3–5 simulation cycles)

The simulation identified several feedback structures which drive changes within the circular food system.

Sustainable Demand Loop

- Enhanced consumer awareness is linked to higher sustainable demand for products that align with principles of circular economy.
- Higher sustainable demand stimulates MSME innovation as well as introducing new processes and

products that meet the criteria of environmental and social sustainability.
- This innovation, in turn, further reinforces sustainable demand, to create a positive feedback loop.

Policy of FLW Reduction Loop
- Stronger policy enforcement leads directly to greater FLW reduction across the supply chain.
- Reduced FLW results in measurable environmental gains.
- These environmental gains can influence policy reinforcement, though the connection is moderated by other factors in the model.

Cross-Link Between Demand and FLW Reduction
- Sustainable demand indirectly supports FLW reduction through MSME innovation that incorporates waste minimization practices.
- The environmental gains from FLW reduction contribute to the overall stability of the circular food system, thus creating interdependencies between consumer-driven and policy-driven feedback loops.

The positive (+) and negative (–) signs indicate the directional effect between variables, to show where increases in one factor led to increases or decreases in another. In the model, positive loops were more dominant, particularly in the consumer awareness–MSME innovation pathway, as illustrated in the following Figure 3.

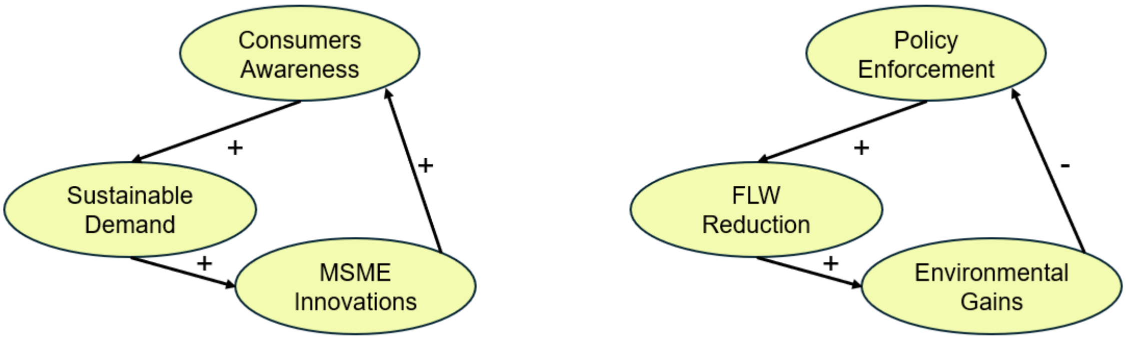

Figure 3. Causal loop diagram

4. Discussion

4.1 Interpretation of Findings from Social Network Analysis

The SNA reveals a fragmented food system structure in which influence is not determined solely by formal authority or direct connectivity. MSMEs and consumers emerge as influential actors despite their peripheral structural positions, thus indicating that systemic influence operates through indirect and second-order connections rather than through centralized control (Lin et al., 2024). Their proximity to highly connected institutional actors permit them to shape behavioral norms, market responses, and redistribution dynamics across the system (Hamam et al., 2021).

This apparent paradox reflects an important socio-technical characteristic of complex food systems: actors positioned outside formal governance hierarchies can still exert substantial influence when embedded in relationally powerful networks. MSMEs function as adaptive intermediaries that translate consumer demand into operational changes, thereby accelerating the diffusion of circular practices (Alonso-Adame et al., 2024). Consumers, through collective behavioral shifts, indirectly pressure upstream actors to adopt more sustainable practices (El Bilali et al., 2019).

Government actors, while central in the structure, display limited embeddedness in everyday interactions within the network. This suggests that regulatory authority alone is insufficient to drive transformation unless coupled with active engagement and coordination with non-state actors (Hasyimi et al., 2024). NGOs and cooperatives play a critical bridging role by connecting grassroots actors with institutional support, thus reinforcing the importance of hybrid governance arrangements for transformation to inclusive food system (Gustafson et al., 2016).

4.2 Interpretation of Results from Agent-Based Modelling

The agent-based simulations indicate that meaningful system-level improvements arise from the interaction of multiple policy levers rather than isolated interventions. Integrated scenarios generate reinforcing feedback loops among consumer behavior, MSME innovation, and institutional responsiveness, to enable non-linear gains in sustainability performance and equity outcomes (Vuthi et al., 2022).

Behavioral adaptation emerges as a key driver of system transformation. Increased awareness among consumers strengthens demand-side signals, hence encouraging MSMEs to invest in circular technologies and waste reduction practices (Denicolai et al., 2021). These changes, in turn, enhance the stability of the overall system and reinforce institutional commitment, hence illustrating how social learning and imitation processes amplify policy impacts over a long period of time (Shishvan & Benndorf, 2019).

In contrast, single-lever interventions tend to produce diminishing returns due to structural constraints and delayed behavioral responses. The simulation highlights the importance of coordinated policy design that simultaneously addresses technological capacity, regulatory alignment, and human behavior to overcome systemic inertia and lock-in effects (Diakosavvas & Frezal, 2019).

4.3 Theoretical Implications

This research built on and extended the theoretical framework of CSCM by embedding it in a socio-technical system. While Farooque et al. (2022), Mahmoud et al. (2025), and Park et al. (2024) highlighted the role of CSCM in reducing environmental impact, this study revealed that the success of CSCM was mediated by actor behavior, institutional dynamics, and social learning as these were dimensions often overlooked in traditional supply chain literature.

The incorporation of macro-ergonomics into food systems aligns with Scheer et al. (2022), who emphasized the importance of designing systems that fit both organizational structures and human capabilities. This is particularly relevant in the context of food systems, where local practices, labor conditions, and cultural values must be harmonized with sustainability objectives (Caron et al., 2018; Esposito et al., 2020; Fortunati et al., 2020; Richardson & Fernqvist, 2024; Varzakas & Smaoui, 2024).

The application of ABM for the human-centered design in food systems remains relatively rare. However, studies such as Mabey et al. (2023) provided precedent for the use of ABM to simulate behavioral complexity in socio-environmental contexts. This research contributes by operationalizing such complexity through an actor-based circular food system model, rendering it more practical for policy and design purposes.

4.4 Policy Implications

The empirical and simulation findings supported several concrete policy recommendations:

(1) Empower MSMEs and Cooperatives: Provide tax relief and targeted grants for the adoption of circular technologies and recognize cooperatives as key actors in local food governance.
(2) Activate Consumer Roles: Launch public campaigns to promote sustainable consumption, reduction in food waste, and local food pride, to be supported by labeling systems and digital nudges.
(3) Bridge Farmers and Consumers: Facilitate farm-to-table models through digital logistics platforms, to integrate real-time supply and demand across regions.
(4) Incentivize Circularity: Implement regulatory frameworks that reward FLW reduction, revalorization of food surplus, and regenerative farming.
(5) Decentralize Policy Implementation: Strengthen local governance bodies (e.g., village-owned enterprises (BUMDes) and village cooperatives) to enable adaptive and context-sensitive food system innovation.

These interventions also aligned with key Sustainable Development Goals (SDGs):

(1) SDG 2: Zero Hunger—via inclusive and equitable access to food.
(2) SDG 12: Responsible Consumption and Production—by reducing waste and increasing circularity; and
(3) SDG 13: Climate Action—through reduction in emissions from FLW and regenerative practices.

4.5 Contributions to Literature

This research contributes to the literature in three primary ways:

Methodologically, it integrated TA, SNA, and ABM within a unified socio-technical framework to demonstrate how qualitative insights could inform quantitative modeling for system transformation.

Substantively, it contextualized the principles of circular supply chain within the realities of Indonesia's food system, in order to highlight the embeddedness of cultural, institutional, and behavioral factors.

Practically, it provided a transferable model that could guide policy design in other Global South contexts, which were facing similar systemic fragmentation, FLW challenges, and governance constraints.

This study thus bridged the gap between system thinking and policy practices, thus offering a replicable blueprint for the transformation to inclusive and sustainable food system.

5. Conclusions

This study demonstrated that integrating TA, SNA, and ABM provided convergent evidence of the dynamics in Indonesia's food system. The results showed that the system was fragmented yet remained highly transformable.

Qualitative analysis identified persistent challenges, including limited technology and infrastructure, low consumer literacy, socio-economic disparities, regulatory gaps, weak collaboration, and entrenched cultural behaviors. These themes correspond to a sparse and modular network structure in which government and NGOs act as critical brokers. MSMEs and consumers exert notable influence despite their peripheral positions, while farmers and cooperatives form clusters with limited market feedback.

Simulation results confirmed that single-lever policy interventions yielded only incremental improvements. In contrast, a combined intervention package involving technology subsidies, regulatory enforcement, and education (S5) produced the most substantial outcomes. These included significant reductions in FLW, higher adoption of circular practices, and improved equity and stakeholder satisfaction. The improvements were driven by reinforcing demand–innovation loops and institutional feedback mechanisms.

The findings extended circular supply chain theory by explicitly embedding behavioral dynamics, institutional relationships, and social learning processes. In addition, the study foregrounded the role of macro-ergonomics in ensuring alignment between human capabilities and system design. Key priorities for food system transformation include empowering MSMEs and cooperatives, activating consumers as agents of change, bridging farmers with markets, incentivizing circular practices, and decentralizing implementation. Together, these strategies support progress toward SDGs 2, 12, and 13.

6. Recommendations

This research provided the following recommendations: (i) adopt an integrated S5-style package by combining technology subsidies, regulatory enforcement, and consumer education while strengthening cooperatives/NGOs as bridging actors among farmers, MSMEs, and consumers; (ii) close last-mile logistics and literacy gaps (micro cold-chain hubs, traceability, "waste-wise" labeling, and digital nudges); (iii) introduce circularity incentives (tax credits, green procurement, and phased FLW reporting); and (iv) decentralize delivery to village-owned enterprises (BUMDes) and cooperatives with performance-based flexible funding.

Phase roll-out: 0–6 months (tech grants, campaigns, open data dashboard with ABM-in-the-loop), 6–18 months (regulatory sandbox, farm-to-table e-logistics, and cooperative capacity building), 18–36 months (institutionalize green procurement and scale nationally).

Track core KPIs (FLW ↓ toward ~40% by 36 months, circular adoption ≥50%, rising equity and satisfaction) and network metrics (more cross-cluster ties). Mitigate risks of incentive gaming or small-actor exclusion via third-party verification, random audits, and inclusive design.

Author Contributions

Conceptualization, H.P. and R.A.A.A.P.; methodology, H.P. and R.A.A.A.P.; software, R.A.A.A.P. and T.I.; validation, H.P., R.A.A.A.P., T.I., and F.F.; formal analysis, R.A.A.A.P. and T.I.; investigation, R.A.A.A.P. and F.F.; resources, H.P.; data curation, R.A.A.A.P.; writing—original draft preparation, R.A.A.A.P.; writing—review and editing, H.P., T.I., and F.F.; visualization, R.A.A.A.P. and T.I.; supervision, H.P.; project administration, H.P.; funding acquisition, H.P. All authors have read and agreed to the published version of the manuscript.

Funding

This study received financial support from the Directorate of Research, Technology, and Community Service, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, through the 2025 Research Grant Program (Grant No.: 126/C3/DT.05.00/PL/2025).

Data Availability

All data supporting the findings of this study are available within the manuscript and the cited references.

Conflicts of Interest

The authors declare no conflict of interest.

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