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A Risk-Weighted Multi-Criteria Decision Model for Prioritizing Food Loss and Waste Management Strategies in Developing Countries

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Abstract

Developing countries face persistent challenges in reducing food loss and waste (FLW), threatening food security, environmental sustainability, and economic resilience. This study presents a systematic review of 19 peer-reviewed articles from the Scopus database, supplemented by global datasets from FAO, UNEP, and the World Bank, to validate impact and feasibility variables. This study proposes a hybrid decision model that combines the Multi-Criteria Decision-Making (MCDM) framework with Failure Mode and Effects Analysis (FMEA) to evaluate FLW strategies across five criteria: economic, environmental, social, scalability, and implementation complexity, grouped into behavioral, technological, processing, systemic, and policy-based categories. The evaluation applied entropy-derived weights and ranked the TOPSIS method, with risk dimensions (severity, occurrence, and detection) adjusting feasible weights. The results indicate that behavioral strategies rank highest due to strong social resonance and moderate risk, making them suitable for early-stage interventions. Processing strategies offer the best balance between environmental performance and operational viability, while systemic and policy-based strategies, though theoretically robust, face high complexity and institutional dependencies. This study presents a reproducible, risk-sensitive prioritization framework for policymakers and practitioners in the Global South, supporting the informed selection of FLW interventions aligned with SDG 12.3 by aligning sustainability performance with real-world feasibility.

Keywords
food loss and waste, developing countries, MCDM, FMEA, TOPSIS

1. Introduction
Food loss and waste (FLW) represent a significant global challenge, particularly for developing countries, where food insecurity, environmental degradation, and inefficient systems coexist (Badeenezhad et al., 2024). According to the United Nations Environment Programme (UNEP), approximately 931 million tonnes of food are wasted annually worldwide, with a substantial portion occurring in low- and middle-income countries due to supply chain inefficiencies, poor storage, and inadequate policy implementation (UNEP, 2021).

The United Nations has emphasized the urgency of addressing food loss and waste (FLW) through Sustainable Development Goal (SDG) 12.3, which targets a 50% reduction in per capita global food waste at the retail and consumer levels, as well as a reduction in food losses along production and supply chains, by 2030. This goal underlines not only the environmental impact of FLW, which accounts for 8-10% of global greenhouse gas (GHG) emissions, but also its economic and social dimensions, including rising food prices and a decline in labor productivity (FAO, 2015).

FLW management in the Global South faces structural challenges, such as weak institutional capacity, limited access to technology, and low public awareness, which have led several studies to propose interventions ranging from behavioral change to policy reforms. However, these approaches are studied individually without a comparative evaluation across the dimensions of economic feasibility, environmental impact, and social acceptance. To address this gap, this study constructs its central research question using the POE (Population-Outcome-Exposure) framework, which helps align the cope of analysis with context-specific challenges and measurable outcomes. The population component (P) refers to developing countries, including emerging economies within the Global South, which face a disproportionately high burden of food system inefficiencies. The outcome dimension (O) focuses on the economic, environmental, and social impacts associated with FLW. The exposure element (E) encompasses the variety of FLW-related practices, ranging from waste reduction and processing to treatment and disposal, that are available or proposed in this context. This formulation ensures that the study remains grounded in the realities of implementation while targeting outcomes that align with sustainability priorities.

Based on this framework, the study formulates the following research question; "What type of FLW management strategy delivers the most appropriate and optimal outcomes, economically, environmentally, and socially, for developing countries?".

1.1 Objectives

This research question highlights a critical gap in existing works of literature: previous studies provide fragmented findings without offering a comprehensive, decision-oriented synthesis. Researchers utilized sustainametric modeling to evaluate system performance (Aboginije et al., 2022), explored digital circular economy tools for mitigation (de Souza et al., 2021), assessed the feasibility of composting in specific regions (Lim et al., 2019), and quantified postharvest losses through large-scale surveys (Lu et al., 2022). However, none of these studies compare approaches across multiple dimensions or weigh them against practical implementation risks. This gap drives the need to build an evaluation framework that directly considers economic feasibility, environmental impact, and social acceptance in managing FLW in developing countries.

This study develops an integrated analytical framework that combines Multi-Criteria Decision Making (MCDM) with a structured risk-based evaluation using Failure Mode and Effects Analysis (FMEA). Unlike conventional approaches that rely heavily on subjective expert weighting, this study employs the Entropy Weight Method (EWM) to assign objective weights based on informational diversity. It applies the TOPSIS method to rank strategy alternatives to an ideal solution. Finally, it adjusts implementation feasibility through risk calibration using empirical Risk Priority Numbers (RPNs). The hybrid mode directly assesses both sustainability performance and field-level feasibility, effectively addressing a critical intersection that sustainability-focused evaluations often overlook. The resulting framework provides a transparent, reproducible, and risk-sensitive prioritization tool for selecting FLW strategies in the Global South, aligning with SDF 12.3 and addressing real-world constraints.

2. Literature Review

Research on FLW management in developing countries has evolved significantly over the past decade, addressing diverse aspects but lacking an integrative evaluation.

2.1. Behavioral Strategies

Behavioral interventions highlight how household decisions to reduce FLW often depend on emotional responses and cognitive perceptions, particularly among younger generations, who contribute to over 60% of global food waste (Attiq, Chau, et al., 2021; UNEP, 2021). Financial pressure and psychological concerns also influence consumer tendencies, with actual behavior frequently diverging from initial intentions (Attiq, Chu, et al., 2021). Local structural conditions and cultural norms have a significant influence on food disposal patterns at the household level in developing countries, where interventions often depend on the surrounding socio-economic context (Montero-Vega et al., 2024). Consumer behavior has also shifted during recent global crises, such as the pandemic and economic downturns, leading to increased awareness of food value and more cautious consumption habits (Pocol et al., 2023).

2.2. Technological Interventions

Technology plays a crucial role in enhancing the efficiency and traceability of food supply chains, particularly in developing countries where postharvest losses remain substantial. Digital platforms have enabled better inventory control, predictive analytics, and logistics coordination, thereby reducing inefficiencies along the value chain

(Chauhan, 2020). Circular economy principles further extend these benefits by integrating waste valorization and resource recovery through digital infrastructure in emerging economies (de Souza et al., 2021).

Tech-based strategies not only enhance economic performance but also contribute to environmental goals by reducing avoidable losses before final disposal. The combination of digital tools and circular marketing approaches strengthens upstream intervention while promoting consumer awareness. However, implementation complexity varies depending on digital infrastructure, human capital, and investment readiness, especially in regions with uneven technological access (Sahoo et al., 2024).

2.3. Processing and Biotechnological Approaches

Processing-based strategies provide practical solutions for converting food waste into valuable products, thereby contributing to both environmental mitigation and economic recovery. Integrated composting systems linked to organic farming demonstrate strong feasibility in community settings, offering co-benefits in soil health, waste reduction, and sustainable agriculture (Lim et al., 2019). Plant-based waste materials can also serve as functional inputs for environmental remediation, such as the removal of heavy metals from contaminated water, aligning with circular economy goals that emphasize valorization and reuse (Soon et al., 2022). Biotechnological advancements further expand the potential of waste processing by enabling the conversion of organic residues into high-value bio-products while simultaneously reducing the environmental burdens associated with unmanaged food waste (Sufficiency et al., 2022).

2.4. Systemic and Supply Chain Interventions

Systemic approaches address FLW at a structural level, targeting inefficiencies embedded across entire supply chains. Value stream mapping has revealed critical loss hotspots and data gaps in the grain-based product cycle, supporting targeted interventions in the production and processing phases (Ghaziani et al., 2023). Cold chain disruptions often result in significant product deterioration, particularly in countries with inadequate energy management and insufficient storage infrastructure. Assessing energy use and optimizing cold storage logistics contribute directly to loss prevention and shelf-life extension (Karacan et al., 2023). Supply chain redesign supports resource efficiency and environmental sustainability by enhancing material flow and improving recovery potential throughout the food system (Krishnan et al., 2020). Efforts to reduce postharvest losses also enhance food security outcomes, particularly in developing countries, where the food loss rate can be as high as 13% before reaching consumers (Khan et al., 2024).

2.5. Policy-Oriented Solutions

Policy-based strategies aim to achieve systemic transformation through regulations, fiscal tools, and long-term planning, addressing FLW at both national and global levels. Waste management systems must respond to projected increases in global waste, which may reach 3.40 billion tons by 2050, by enhancing performance measurement and lifecycle optimization in urban infrastructures (Aboginije et al., 2022). Macroeconomic modeling reveals that food waste has a significant impact on global food prices, agricultural production, and the use of natural resources, underscoring the need for integrated policy responses that encompass diverse income groups (Lopez Barrera & Hertel, 2021). GHG emissions linked to FLW, estimated at 8-10% of global totals, can be mitigated through climate-focused policies that align with food security objectives, especially in emerging economies (Vázquez-Rowe et al., 2021). Public food management behaviors also respond to policy shocks. For example, the Covid 19 pandemic altered household food practices in developing countries, underlining the importance of adaptive governance that reflects changing social dynamics (Yetkin Özbük et al., 2022).

Despite the breadth of insights, the reviewed literature shares two key limitations. First, no study simultaneously assesses FLW management strategies across the three dimensions of economy, environment, and society using an objective multi-criteria framework. Prior works often rely on descriptive scoring or narrative reviews that lack reproducibility and comparability across contexts. Second, implementation risks, such as failure rates, coordination difficulties, and detectability of bottlenecks, are largely absent from current evaluation models. This omission reduces the practical applicability of many proposed interventions, particularly in regions where institutional fragility and resource constraints are prevalent.

3. Methods

This study adopted an integrated multi-phase framework to extract, classify, and evaluate FLW management strategies in developing country contexts. The approach combines qualitative content synthesis, objective MCDM, and risk-based prioritization using FMEA, enabling both analytical rigor and policy relevance. This structure flows established best practices in evidence synthesis (Tranfield et al., 2003), sustainability assessment (Sala et al., 2015), and structured decision analysis (Belton & Stewart, 2002).

3.1 Data Extraction and Classification

The first phase involved the systematic screening and review of 19 peer-reviewed journal articles addressing FLW management. The study applied a structured analysis process to extract four analytical components from each study: the strategy type, intervention level, reported outcomes, and contextual enabler. It classified the strategy types based on typologies used in the sustainability innovation literature (Markard et al., 2012). It grouped them into five categories: economic, environmental, and social, in line with the triple bottom line perspective (Elkington, 1999). It also documented contextual factors such as governance support, infrastructure readiness, and socio-cultural dynamics to ensure that the classification recognized implementation realities.

Strategy	Description
Behavioral	Includes interventions such as consumer awareness, educational campaigns, and psychological nudges aiming to reduce food waste at the household or retail level
Technological	It encompasses digital solutions, including IoT monitoring, blockchain-based traceability, and mobile applications for food redistribution.
Processing	It involves valorization of food waste through composting, anaerobic digestion, or conversion into bio-based materials.
Systemic	Focuses on postharvest improvements, supply chain optimization, and cold chain development to minimize losses before they become waste.
Policy-Based	Includes legal frameworks, fiscal incentives, food donation laws, and landfill restrictions to shape systemic behavior change.

This study compiled all extracted data into a structured matrix to facilitate cross-case comparability and prepare for formal evaluation. This process aligns with the logic of qualitative comparative analysis (QCA) and matrix-based evidence synthesis (Rihoux & Ragin, 2009).

3.2 Construction and Evaluation Criteria

Building on the structured data, this study developed a set of sustainability-oriented evaluation criteria based on both the literature and international frameworks. It defined three criteria: economic feasibility, environmental performance, and social relevance. This three-dimensional structure flows the principles of integrated sustainability assessment (Gibson et al., 2013) in FLW evaluation studies (Papargyropoulou et al., 2014).

Economic feasibility considers cost-efficiency, capital investment, and operational viability. Environmental performance encompasses emission mitigation, resource recovery, and waste diversion, consistent with circular economy metrics (Kirchherr et al., 2017). Social relevance encompasses public acceptance, behavioral change potential, and cultural fit, reflecting insights from socio-technical systems theory and behavioral intervention design (Geels, 2002; Michie et al., 2011).

In addition to the core sustainability criteria, this study incorporates two practical criteria: scalability and implementation complexity. Scalability reflects the potential for widespread adoption across different regions and scales, while implementation complexity captures technical, institutional, and financial barriers encountered during deployment. These additions ensure that the model accounts for real-world feasibility, particularly in low-capacity environments typical of many developing countries.

The scoring process employed a triangulated approach that combined coded funding from the literature, benchmark indicators from international datasets (e.g., the UNEP Food Waste Index, the FAO Food Loss Index), and contextual relevance based on implementation conditions in developing countries. To avoid subjectivity and ensure methodological transparency, this study applied the Entropy Weight Method (EWM) to determine the relative importance of each criterion. Entropy analysis captures the information diversity of each criterion based on variation across strategies. Criteria with greater dispersion receive higher weights, reflecting their stronger discriminatory power in the evaluation process.

3.3 Performance Evaluation via TOPSIS

Following weight determination, the study applied the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to rank FLW strategies based on their sustainability performance across five criteria: economic effectiveness, environmental impact, social acceptance, scalability, and implementation complexity. These five evaluation steps followed the standard TOPSIS procedures as established in previous works (Tzeng, 2011; Wang & Elhag, 2006). The first step involved normalizing the decision matrix using vector normalization to eliminate unit inconsistencies across criteria:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (1)$$

Second, multiplying each normalized value by its corresponding entropy-derived weight w_{ij} to obtain the weighted normalized matrix:

$$v_{ij} = r_{ij} \times w_{ij} \quad (2)$$

Third, identifying the ideal and anti-ideal solutions. The model identified the positive ideal solution, A+ (representing the best values), and the negative ideal solution, A- (representing the worst values), across all criteria, followed by the fourth, computing Euclidean distances from each strategy to the ideal and anti-ideal points.

$$S_i^+ = \sqrt{\sum (v_{ij} - v_j^+)^2}, \qquad S_i^- = \sqrt{\sum (v_{ij} - v_j^-)^2} \quad (3)$$

Moreover, last, calculate the closeness coefficient (CC) to derive a raw performance score.

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (4)$$

This approach enables a transparent and systematic comparison of strategies based on multi-dimensional performance attributes.

3.4 Integration with Risk-Based Evaluation

The final phase introduced a risk-sensitive dimension using FMEA, allowing structured identification and quantification of potential failure modes based on three dimensions: severity (the magnitude of impact if the strategy fails), occurrence (the likelihood of failure or implementation challenge), and detection (the ability to identify and mitigate risk early). The study assigned each FLW strategy as a composite index score, known as the Risk Priority number, by multiplying its respective severity, occurrence, and detection values.

The study calculated the final score of each strategy by dividing its closeness coefficient (CC), obtained through the TOPSIS method, by one plus its associated risk score. The model expresses risk score as the RPN. As the level of risk increases, the denominator becomes larger, resulting in a lower final score for high-risk strategies. In this way, the model penalizes theoretically appealing strategies that are less feasible in practice. This risk-adjusted approach ensures that the final ranking reflects not only conceptual desirability but also practical implementability, which is especially critical in the context of developing countries.

4. Data Collection

4.1 Literature Search and Identification Strategy

This study draws on two primary data sources: peer-reviewed literature and open-access global datasets. It selects the peer-reviewed literature through a systematic search using the Scopus database. The search strategy combined five keyword clusters to capture relevant studies on FLW management in developing contexts. These keyword clusters include FLW terms (food loss" OR "food waste" OR "waste reduction"), treatment strategies ("treatment" OR "management" OR "disposal" OR "processing"), economic and social considerations ("econom*" OR "cost" OR "financial" OR "monetary" OR "effectiveness" OR "efficien*" OR "social"), environmental aspects ("environmental" OR "ecological" OR "sustainability" OR "impact"), and geographical scope terms related to developing countries ("developing countr*" OR "global south" OR "emerging economy" OR "emerging countr*"). These keywords directly support the research objectives, which aim to identify the most optimal FLW management strategies across economic, environmental, and social dimensions in developing countries. The initial search produced 269 records.

4.2 Screening and Selection Process

This study then applied a PRISMA-based screening process to refine the datasets in sequential steps. First, it filtered the records by publication year, keeping only studies published between 2019 and 2025, and by language, focusing exclusively on English-language publications. Second, it retained only articles that had reached the final publication stage, excluding any conference abstracts, early access versions, or reviews in progress. Third, it limited the selection to open-access articles to ensure the transparency and replicability of data, which narrowed the dataset to 49 articles. After obtaining this subset, it conducted a more detailed screening by reviewing titles, abstracts, and full-text articles to assess the relevance of each, focusing on whether the studies addressed the economic, environmental, or social impacts of FLW management. This screening process resulted in a final set of 19 articles selected for in-depth synthesis and analysis.

4.3 Supplementary Data Sources

To strengthen the analysis and ensure broader contextual validity, this study also incorporates open-access secondary data from four international sources. These include the FAO Food Loss and Waste Platform, the UNEP Food Waste Index Report, the World Bank's "What a Waste 2.0" Report, and the WRI Food Loss and Waste Protocol. These global datasets provide standardized benchmarks on food loss volumes, GHG emissions, treatment costs, and implementation patterns, enabling the calibration and validation of the model's scoring process.

5. Results and Discussion

This section presents the results of the integrated evaluation framework, which combines entropy weighting, the TOPSIS method, and risk-based calibration using FMEA. The objective is to identify the most feasible FLW management strategies in developing countries by measuring their sustainability performance and implementation risk.

5.1 Numerical Results

5.1.1. Entropy Weighting and Initial Strategy Performance

The study employed entropy weighting to assess the relative importance of each evaluation criterion. It assigned objective weights based on the degree of information variation among strategies for each criterion and incorporated them into the TOPSIS evaluation framework as described in the Method section.

Table 1 presents the selected peer-reviewed studies included in this research, classifying them by the type of FLW management strategy they propose. It links strategy to one or more sustainability evaluation criteria: economic impact (C1), environmental benefit (C2), social acceptance (C3), scalability (C4), and implementation complexity (C5). This classification serves as the foundational reference for subsequent risk scoring and decision analysis.

Table 1. Classification of FLW Management Strategies by Literature Source

No	Article	Strategy Type	Evaluation Criteria
1	(Aboginije et al., 2022)	Policy-Based	C4, C5
2	(Attiq, Chau, et al., 2021)	Behavioral	C1, C3
3	(Attiq, Chu, et al., 2021)	Behavioral	C3
4	(Chauhan, 2020)	Technological	C1, C2, C3, C5
5	(de Souza et al., 2021)	Technological	C1, C4
6	(Ghaziani et al., 2023)	Systemic	C2
7	(Karacan et al., 2023)	Systemic	C3
8	(Khan et al., 2024)	Systemic	C4, C5
9	(Krishnan et al., 2020)	Systemic	C2, C4
10	(Lim et al., 2019)	Processing	C3, C4, C5
11	(Lopez Barrera & Hertel, 2021)	Policy-Based	C1, C5
12	(Lu et al., 2022)	Systemic	C1, C5
13	(Montero-Vega et al., 2024)	Behavioral	C3, C5
14	(Pocol et al., 2023)	Behavioral	C2, C4
15	(Sahoo et al., 2024)	Technological	C5
16	(Soon et al., 2022)	Processing	C2, C4
17	(Sufficiency et al., 2022)	Processing	C1, C2, C5
18	(Vázquez-Rowe et al., 2021)	Policy-Based	C2
19	(Yetkin Özbük et al., 2022)	Policy-Based	C3

The classification indicates that systemic and policy-based strategies are the most frequently addressed in the literature, often associated with scalability (C4) and implementation complexity (C5), reflecting recognition of their potential broad impact as well as the inherent challenges in operationalizing such strategies in developing countries. Behavioral strategies are primarily linked to social (C3) and economic (C1) criteria, emphasizing ease of adoption and cost-effectiveness. Technological and processing strategies encompass a broader range of criteria, underscoring their cross-cutting relevance across multiple domains. Overall, the literature reveals a multi-dimensional focus, supporting the need for an integrated evaluation approach that balances sustainability objectives with contextual feasibility.

Building on this classification, the study proceeded to calculate the entropy values for each criterion to determine their relative influence across strategy types. It integrated the weights into the TOPSIS model to produce the closeness coefficient for each strategy (Table 2).

Table 2. Entropy Values, Derived Weights, and Resulting Closeness Coefficient for Each Strategy

Strategy	Entropy Value (e_{ij})	Diversification (d_{ij})	Weight (wij)	Closeness Coefficient (CC)
Behavioral	0.9165	0.0835	0.4063	0.5908
Processing	0.9630	0.0370	0.1803	0.3771
Systemic	0.9630	0.0370	0.1803	0.3771
Technological	0.9697	0.0303	0.1474	0.2389
Policy-Based	0.9824	0.0176	0.0857	0.1573

The results show that the behavioral strategy achieved the highest CC value (0.5908), indicating its strong overall sustainability performance across all five criteria, especially in socially driven contexts. Processing strategies and systemic approaches yield a moderate correlation coefficient (0.3771), particularly in terms of environmental performance and scalability. Technological strategies ranked lower in CC (0.2389), reflecting limitations in social acceptance and implementation complexity. Policy-based strategies scored the lowest CC (0.1573) due to high institutional dependencies and limited feasibility at the operational level.

5.1.2. Risk Assessment via FMEA (S-O-D Scoring)

Building on the classification strategies and their associated criteria, Table 3 presents the empirical calibration of risk values derived from FMEA. This study scored each selected study across three dimensions, Severity (S), Occurrence (O), and Detection (D), based on the contextual justifications provided in the literature. These qualitative rationales reflect real-world barriers and monitoring challenges encountered in implementing FLW strategies in developing countries. This calibration serves as the basis for calculating the RPN, which subsequently informs the composite evaluation model that combines risk factors with sustainability performance metrics.

Table 3. Severity, Occurrence, and Detection (S-O-D) Scores Justifications from Selected Literature

Article	S	O	D	S Score Consideration	O Score Consideration	D Score Consideration
(Aboginije et al., 2022)	9	7	6	Projected 3.4 billion tons of waste by 2050 (World Bank)	Substantial enforcement barriers in low-governance areas	Weak feedback loops
(Attiq, Chau, et al., 2021)	7	8	5	60% FLW from households (UNEP)	Behavior change is inconsistent and difficult to sustain in practice	Impact is measurable but requires long-term observation and surveys
(Attiq, Chu, et al., 2021)	6	7	5	Moderate impact, individual-level drivers	High resistance—both psychological and financial	Requires consistent tools
(Chauhan, 2020)	8	7	4	Digital tools disrupt postharvest	Moderate-to-high risk due to infrastructure/user limits	Failures traceable via system data logs
(de Souza et al., 2021)	7	6	5	CE tools reshape flows, tech-dependent	Implementation risk is moderate due to emerging business models	Monitoring is possible via platform data and transaction metrics
(Ghaziani et al., 2023)	6	7	6	Sectoral disruptions, not always systemic	Multi-level coordination issues can delay or derail efforts	Data gaps and limited real-time indicators

(Karacan et al., 2023)	5	6	5	Energy affects quality, not total supply	Moderate risk due to technical but solvable implementation needs	Measurable via energy and cold chain monitoring systems
(Khan et al., 2024)	9	8	7	13% postharvest loss (FAO)	Multiple vulnerable stages from harvest to market in low-income areas	Losses are often unrecorded, and the data infrastructure is weak
(Krishnan et al., 2020)	8	7	6	Supply chain redesign impacts GHG	System overhauls require coordination and have moderate-to-high risk	Detection requires integrated performance monitoring tools and metrics
(Lim et al., 2019)	7	6	5	Composting improves soil, cuts landfill	Implementation is feasible but depends on local acceptance and infrastructure.	Compost output and waste diversion rates can track performance.
(Lopez Barrera & Hertel, 2021)	8	7	6	FW affects systems pricing	Global interventions are complex and need multi-level coordination	It is not easy to detect policy success without extensive economic modeling
(Lu et al., 2022)	9	8	7	Up to 14% loss in China (primary data)	High risk of inefficiency due to system fragmentation and volume scale	Loss detection relies on detailed field surveys and supply chain mapping
(Montero-Vega et al., 2024)	7	7	5	Households impact municipal FLW	Behavior change in households is moderately uncertain	Longitudinal household data to monitor behavior shifts
(Pocol et al., 2023)	6	6	5	Crisis-driven consumer FLW shifts	Behavior rebound effects post-crisis are moderately likely	Detection is feasible through a pre-and post-survey comparison
(Sahoo et al., 2024)	8	7	6	Tech improves logistics processing	High dependency on digital infrastructure and logistics networks	Performance traceable via digital monitoring and logistics data
(Soon et al., 2022)	5	5	4	Localized environmental benefits	Moderate adoption risk due to the specificity of technology	Effectiveness is measurable in water quality outputs
(Sufficiency et al., 2022)	7	6	5	Biotech recovers organic waste	Moderate risk tied to technology complexity and cost	Monitoring is possible via output/productivity metrics
(Vázquez-Rowe et al., 2021)	9	8	7	FLW causes 8–10% GHG (UNEP/IPCC)	Policy failure disrupts climate commitments	Detection complex due to diffuse
(Yetkin Özbük et al., 2022)	6	7	5	The pandemic disrupted household FLW	The behavioral-political interface creates mid-range risk	Change is traceable via comparative household-level studies

The justification data reveals clear patterns regarding the origin and strength of evidence in assessing risk. Macro-level institutional data, such as projections from the World Bank, FAO, or UNEP, support several high-severity scores (e.g., S = 9). These global sources provide robust evidence of system-wide impacts, such as billions of tons of projected waste and substantial contributions of FLW to GHG emissions. Such sources enhance the credibility and generalizability of severity assessments. Occurrence scores often rely on policy, behavioral, or infrastructure barriers cited in the literature. For example, several studies, such as Khan et al. (2024) and Attiq, Chu, et al. (2021), reference systemic vulnerabilities or behavioral inertia; however, the justification primarily stems from observational patterns or postulated barriers, which, while valid, introduce moderate uncertainty. Detection score justifications often reflect limitations in the data system or measurement challenges and are most frequently based on methodological constraints acknowledged by the authors, such as the difficulty of tracking behavioral shifts over time or the absence of real-time institutional feedback loops. In many cases, these justifications are qualitative, highlighting the lack of structured data infrastructures, especially in low- and middle-income contexts.

This differentiation in data sources between empirical-statistical evidence, contextual analysis, and theoretical inference suggests a varying degree of reliability and objectivity across the S-O-D spectrum. These underlying assumptions are crucial when interpreting the resulting RPN values and comparing implementation risk across strategy types (Table 4).

Table 4. FMEA-Based Risk Assessment

Strategy	Severity (S)	Occurrence (O)	Detection (D)	RPN (S×O×D)
Behavioral	6,5	7,0	5,0	228
Processing	6,3	5,7	4,7	167
Systemic	7,4	7,2	6,2	330
Technological	7,7	6,7	5,0	256
Policy-Based	8,0	7,3	6,0	348

Policy-based and systemic strategies demonstrated the highest risk levels, with RPNs exceeding 300, mainly due to difficulty in coordination, high dependency on institutional readiness, and limited detectability of failure points. In contrast, processing had the lowest RPN, suggesting that it is relatively more controllable, monitorable, and adaptable for developing regions.

5.1.3. Risk Weight Calculation and Integration

To incorporate risk into performance evaluation, this paper used the inverse of the RPN, assigning a proportional weight. These weights were normalized to ensure consistency across all strategies and facilitate comparison (Table 5).

Table 5. Risk-Adjusted Score and Final Ranking

Strategy	Closeness Coefficient (CC)	RPN	Risk-Adjusted Score	Final Rank
Behavioral	0.5908	228	0.0026	1
Processing	0.3771	167	0.0022	2
Systemic	0.3771	330	0.0011	3
Technological	0.2389	256	0.0009	4
Policy-Based	0.1573	348	0.0005	5

The integrated analysis of the closeness coefficient, implementation risk, and final risk-adjusted score reveals the distinct characteristics of each FLW management strategy. Behavioral strategies achieved the highest closeness coefficient and maintained a moderate risk level, resulting in a leading risk-adjusted score that indicates strong alignment with sustainability goals while remaining practical for implementation. Their high social acceptability, ease of deployment, and compatibility with educational and awareness-based initiatives make them ideal as foundational strategies, especially in community-level or household-focused contexts.

Processing and technological strategies, such as composting, valorization, and small-scale bioconversion, ranked second in both CC (0.3771) and final score (0.0022), supported by the lowest RPN among the top-performing options (167). These strategies combine substantial environmental benefits with relatively low implementation barriers, making them highly scalable and well-suited for short to mid-term programs, particularly in semi-urban or municipal systems with existing waste infrastructure.

Systemic strategies also demonstrated strong sustainability performance, but their feasibility diminished significantly when considering risk. With an RPN of 330, their risk-adjusted score dropped to 0.0011. These strategies often require complex logistics, institutional collaboration, and cross-sector coordination, conditions that are rarely present in low-capacity environments. However, systemic approaches offer long-term, transformational potential that is not ideal for near-term deployment unless substantial institutional support is secured.

Technological strategies, including digital traceability platforms, smart logistics, and sensor-based systems, resulted in lower CC (0.2389) and a moderately high RPN (256), leading to a risk-adjusted score of 0.0009. While these solutions offer innovation and efficiency, they depend heavily on infrastructure readiness and skilled technical personnel. Their sustainability lies more in mid to late-stage interventions or urban contexts with stronger digital maturity.

Finally, policy-based strategies recorded the lowest CC (0.1573) and the highest RPN (348), resulting in the weakest risk-adjusted score of 0.0005. Despite their conceptual importance, such as regulations, national targets, or fiscal incentives, these approaches require strong institutional frameworks, stable governance, and enforcement capacity. In developing countries where such prerequisites are often lacking, policymakers should position policy strategies as long-term structural tools instead of immediate operational interventions.

5.1.4. Integrated Risk-Adjusted Prioritization Framework

The decision-making model below illustrates the integration of evaluation and risk adjustment mechanisms, resulting in a composite prioritization of strategies (Figure 1).

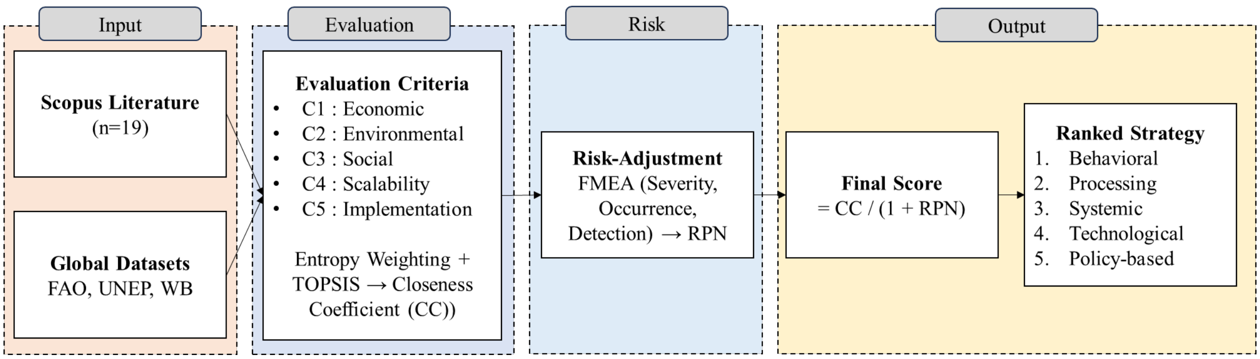

Figure 1. Risk Adjustment Decision Framework for FLW Decision Planning

The diagram illustrates a stepwise decision model that integrates input data, evaluation strategies using multi-criteria analysis, and risk adjustment via FMEA. This framework enables the prioritization of interventions that balance sustainability impact and implementation risk in developing country contexts.

5.2 Graphical Results

Figure 2 illustrates the comparison between the CC and RPN across five FLW management strategies. The blue bars represent the CC, which reflects the sustainability performance of each strategy, while the red line indicates the RPN, measuring implementation risk. Behavioral strategies exhibit the highest CC with moderate risk, making them highly favorable. In contrast, policy-based strategies show the highest and the lowest CC, indicating strong institutional dependency and limited feasibility. This figure highlights the importance of incorporating risk into the prioritization of FLW strategies, particularly in developing countries.

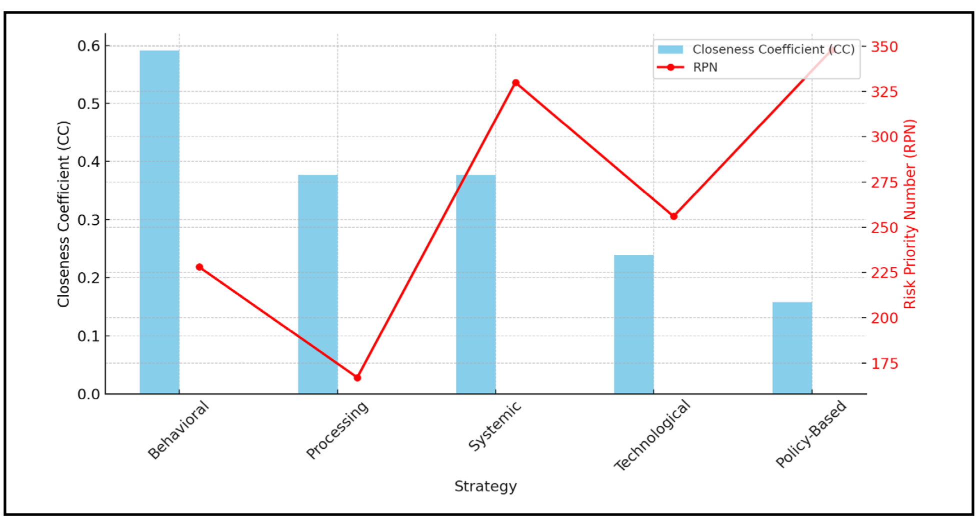

Figure 2. Comparative Visualization of Closeness Coefficient and Risk Priority Number (RPN)

5.3 Proposed Improvements
The analytical results reveal a nuanced understanding of FLW management strategies across developing countries. While the final scores quantitatively rank the alternatives, the qualitative implications—particularly those involving trade-offs, contextual constraints, and systemic alignment —require deeper interpretation.

5.3.1. Strategic Interpretation of Results
Behavioral strategies demonstrated the highest closeness coefficient and delivered the top risk-adjusted score, confirming their strong fit for contexts with limited resources. Their social acceptability, ease of deployment, and compatibility with educational or campaign-based initiatives make them ideal as foundational strategies, particularly at the household or community level. However, their isolated use may not substantially reduce FLW volumes unless integrated into broader systematic interventions.

Processing strategies also exhibited robust performance, with their relatively low RPN and solid CC values highlighting their dual advantage: environmental effectiveness and operational feasibility. Composting, small-scale valorization, and bioconversion systems represent modular solutions that generate circular benefits from food waste. These interventions are particularly valuable for decentralized implementation in semi-urban or municipal contexts, where local waste infrastructure already exists or can be upgraded with minimal institutional dependency.

Systemic strategies, while conceptually strong, faced major implementation hurdles. Despite their promising sustainability contributions, their high RPN values reflect deep-rooted risk-complex logistics, cross-sectoral coordination, and policy fragmentation that often prevail in low-capacity environments. As a result, these strategies are well-suited for long-term structural transformation but offer limited short-term utility without substantial institutional reinforcement.

Technological strategies, such as digital traceability tools, IoT-based monitoring, and smart logistics, possess strong innovation potential. However, their feasibility remains constrained by infrastructure readiness and gaps in digital literacy. These limitations have relegated their ranking, despite notable sustainability gains. The future implementation of such strategies may require pairing them with enabling investments and workforce training, particularly in urban areas with rapidly evolving technological ecosystems.

Policy-based strategies ranked lowest in both CC and adjusted scores. This outcome reflects not their irrelevance but their strong dependence on institutional maturity, legal enforcement capacity, and long-term policy stability. In settings where these prerequisites are absent, policy-based interventions may prove ineffective unless precise accountability mechanisms and a cross-sectoral commitment support them.

These results suggest that mid-system interventions, those situated between household-level behavior and national policies, tend to strike the most effective balance between sustainability performance and practical feasibility. These strategies serve as functional bridges, translating macro frameworks into actionable programs that deliver measurable, ground-level impact.

5.3.2. Novelty
This study presents novel contributions to the literature on evaluating the FLW strategy in developing countries. It advances an integrative framework by combining MCDM with FMEA. This hybrid model enables the concurrent assessment of strategy performance and feasibility, thereby addressing a critical intersection that sustainability-focused evaluations often overlook. It synthesizes 19 peer-reviewed articles and complements them with global open-access datasets from FAO, UNEP, WRI, and the World Bank. This evidence triangulation enhances analytical robustness and situates the findings within a broader, policy-relevant context, extending beyond the limitations of single-case assessments or conventional meta-reviews. The development of a risk-adjusted prioritization matrix, fully operationalized into a structured scoring system, provides a practical decision support tool. Policymakers, municipal planners, and development agencies can replicate or adapt the framework to rank investment alternatives, align interventions with SDG 12.3 targets, or guide the selection of pilot projects. The use of ordinal scoring, weighted risk adjustment, and transparent aggregation ensures both methodological transparency and replicability.

5.3.3. Implications and Future Research
The results point toward the utility of hybrid strategies that combine technological deployment with behavioral engagement and policy alignment. Instead of relying on a single-mode intervention, sustainable FLW reduction in developing countries may require interlocking actions across levels of governance and implementation. For further inquiry, future studies can expand the framework to include economic valuation metrics, such as cost-benefit ratios or complete lifecycle assessments, to enhance decision-making under budget constraints. Integrating stakeholder-weighted criteria through methods such as the Analytic Hierarchy Process (AHP) or Delphi-based consensus building would also enhance the contextual legitimacy of the scoring model. Moreover, there is significant potential for field-based validation of the model's predictive accuracy. Pilot-testing the top-ranked strategies in varied urban and rural settings would enable real-time feedback loops, providing insight into how well model assumptions align with on-the-ground dynamics. Such iterative validation would strengthen the model's capacity not only as an analytical tool but also as an adaptive policy instrument responsive to localized realities.

5.4 Validation
5.4.1. Consistency Check with Literature Trends
The ranking of strategies aligns with empirical trends reported in the literature. For instance, behavioral strategies consistently emerge as highly feasible in household-level interventions, while policy-based strategies often face institutional barriers, validating the model's final scores.

5.4.2. External Data calibration
Risk values (S, O, D) were cross-validated using global datasets from FAO, UNEP, and the World Bank. The authors used triangulation to avoid speculative assumptions and ensure that the implementation risks reflected observed global patterns (e.g., the What a Waste 2.0 Report and Food Waste Index).

5.4.3. Sensitivity Analysis
This paper conducted a sensitivity analysis by varying the entropy weights by ± 10% to test the stability of the rankings. The final order of the top three strategies remained unchanged, indicating the robustness of the evaluation framework.

5.4.4. Statistical Improvement via Risk Adjustment
The final ranking improved the discriminatory power of the model by penalizing strategies with disproportionately high RPNs. A paired comparison between raw CC scores and risk-adjusted scores shows that high-risk strategies (e.g., policy-based) dropped significantly in rank. In contrast, low-risk strategies (e.g., processing) gained relevance. The authors did not conduct a formal hypothesis test (e.g., t-test); however, the observed effect sizes suggest that the differences are not statistically meaningful.

6. Conclusion
This study presents a comprehensive evaluation model that addresses the unique operational realities of FLW management in developing countries. By combining multi-criteria assessment with a structured risk lens, the framework surpasses conventional strategy ranking and provides a solid foundation for implementation planning.
The analysis confirms that interventions offering mid-system leverage, such as modular technologies and resource-oriented processing methods, outperform top-down regulatory instruments and isolated behavioral efforts when assessed through the dual lens of impact and risk. These strategies stand out not only because of their measurable outcomes but also due to their ability to function effectively in fragmented or capacity-limited governance environments.

Rather than promoting one-size-fits-all solutions, the model supports localized decision-making, offering a flexible structure that stakeholders can adapt to institutional capacities, budgetary limits, and social conditions. It equips planners and policymakers with a transparent method to filter options, justify trade-offs, and allocate resources where both impact potential and execution feasibility align most strongly.

This integrative approach also opens new pathways for adaptive governance. As FLW conditions shift in response to population growth, supply chain modernization, and climate variability, the ability to update strategy evaluations with new data and contextual input becomes essential. This study designs the framework to accommodate such iteration, ensuring its ongoing relevance beyond static policy blueprints.

Ultimately, this research provides a decision-support platform that bridges evidence synthesis with practical prioritization. Its core strength lies in translating diverse forms of knowledge—academic, statistical, and contextual—into actionable insights, thereby supporting more informed, sustainable, and resilient food system interventions across the Global South.

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