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Toward Circular Cattle Supply Chains: A Framework for Waste Valorization, Barrier Prioritization, and Mitigation Strategy Selection

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ABSTRACT

The implementation of the Circular Cattle Supply Chain (CCSC) still faces problems, including suboptimal utilization of cattle waste and by-products, as well as internal and external barriers that hinder the establishment of a circular supply chain. This study aims to analyze opportunities for utilizing cattle waste and by-products and to develop a framework for identifying, prioritizing, and determining strategies to mitigate barriers to CCSC implementation. The study employs a conceptual approach based on a literature review, utilizing relevant secondary data on the circular economy, the utilization of cattle waste, and the multi-criteria decision-making (MCDM) approach. The framework was developed by mapping waste generation points and opportunities for their valorization, followed by the formulation of a barrier analysis flowchart and the selection of mitigation strategies. The results show that waste and byproducts are generated at nearly every stage of the slaughtering process and present opportunities for utilization as biogas, bio-fertilizer, collagen, gelatin, and industrial raw materials. The developed framework uses the Fuzzy Best-Worst Method (FBWM) to determine the weights and priorities of barriers. At the same time, Fuzzy TOPSIS (FTOPSIS) evaluates and selects mitigation strategies based on prioritized barriers. This framework provides an analytical basis for stakeholders to formulate policies and strategies to improve resource efficiency, create added value, and implement sustainable CCSC.

INTRODUCTION

The circular economy (CE) is an approach that emphasizes economic and environmental sustainability in response to the growing consumption of natural resources—particularly non-renewable resources—driven by global population growth [1]. The CE offers a systemic solution to the impacts of the linear "take–make–dispose" production and consumption model through reuse, recycling, resource recovery, and improved material efficiency, all of which align with the achievement of the Sustainable Development Goals (SDGs) [2]. This approach is highly relevant to the livestock sector because production processes generate various byproducts that can be returned to the system as sources of energy, fertilizer, feed, or industrial raw materials [3, 4]. Thus, applying CE in the livestock supply chain not only reduces waste but also preserves the value of resources within the system, creating sustainable economic, environmental, and social benefits.

The meat processing industry, particularly for livestock products, is one of the priority industries in the 2015–2035 National Industrial Development Master Plan (RIPIN) [5], while the meat cattle sector plays a strategic role in supporting Indonesia's food security [6]. East Java is one of the nation's main centers for meat cattle farming [7]. Data from the Central Statistics Agency (BPS) for 2024 show that East Java has the highest beef cattle population and meat production in Indonesia, reaching 3.11 million head and approximately 96,967 metric tons [8]. The scale of these activities also generates significant amounts of byproducts during the slaughter process, while their utilization remains limited [9]. These byproducts include feces, urine, blood, wastewater, hair, hooves, hides, offal, bones, as well as meat trimmings and fat, all of which have broad potential for utilization [10]. Without proper management, this waste can cause water pollution due to excess nitrates and carbon, greenhouse gas emissions, soil degradation due to nutrient accumulation, and health risks to humans and animals [11].

This situation highlights the importance of implementing a circular cattle supply chain (CCSC) to transform waste and byproducts into value-added resources. However, the implementation of the CE faces various internal and external barriers that hinder the transformation of the supply chain toward a more circular system [12]. This issue must be addressed by mapping potential uses of waste to identify valorization opportunities for each byproduct type, accompanied by a framework for analyzing barriers and determining appropriate mitigation strategies. Without a structured approach, the economic potential of waste will remain untapped, the environmental burden will increase, resource efficiency will decline, and integration among supply chain actors will be hindered. In the context of such decision-making, multi-criteria decision-making (MCDM) is relevant because it can evaluate various interrelated criteria that may have differing levels of importance [13]. Therefore, the application of MCDM to analyze barriers and select mitigation strategies is a crucial component in supporting the transformation of the meat supply chain toward a more circular, integrated, and sustainable system.

Various studies have applied MCDM approaches to analyze barriers to CE implementation across various sectors. Afroozi, et al. [14] analyzed CE barriers in Iran's battery sector using an integrated approach combining the Gray Delphi method, the Gray Decision Making Trial and Evaluation Laboratory (DEMATEL), and the Gray Analytic Network Process (ANP), while Liu, et al. [15] examined barriers in the construction sector in Malaysia using the Fuzzy Delphi–Analytic Hierarchy Process (AHP)–Interpretive Structural Modeling (ISM)–Matrice d'Impacts Croisées Multiplication Appliquée à un Classement (MICMAC). In India's manufacturing sector, Majiwala and Kant [16] applied the Spherical Fuzzy Step-wise Weight Assessment Ratio Analysis (SF SWARA)–Spherical Fuzzy Combined Compromise Solution (SF COCOSO), while Humberto, et al. [17] used the Fuzzy Delphi–Best-Worst Method (BWM) to analyze barriers in Brazil's agricultural sector. Debnath, et al. [18] integrated BWM–ISM–MICMAC to evaluate barriers in the electronics manufacturing sector in Bangladesh. Furthermore, Gopan and Balaji [19] used AHP in the automotive industry in India, while Chen, et al. [20] applied Grey-based DEMATEL to analyze barriers in the textile sector in China. These studies indicate an increasing use of MCDM to identify, weight, rank, and organize barriers to CE implementation. However, the approaches reviewed primarily focus on analyzing barriers as standalone decision-making problems. These approaches provide limited integration between opportunities for resource recovery that promote circularity, the prioritization of barriers hindering its implementation, and the

subsequent selection of mitigation strategies. Therefore, the research gap lies not only in the limited application of MCDM to the CCSC but also in the absence of a structured decision-making process that links these three stages within the cattle supply chain.

This integrative gap is highly relevant to CCSC because circularity in the livestock supply chain depends not only on recognizing the potential value of waste and byproducts but also on overcoming barriers to the recovery and reintegration of these resources into the system. CCSC encompasses a series of interrelated activities, including farming, slaughter, byproduct management, waste utilization, and resource recovery. Therefore, identifying valorization opportunities alone does not reveal which implementation barriers require the biggest attention, while simply ranking barriers does not determine which actions should be prioritized to address them. To bridge these disconnected stages of decision-making, this study proposes an integrated framework that sequentially links the mapping of waste and byproduct valorization, the prioritization of barriers using the Fuzzy Best-Worst Method (FBWM), and the selection of mitigation strategies using Fuzzy TOPSIS (FTOPSIS). FBWM identifies which barriers are relatively more critical, while FTOPSIS evaluates which mitigation strategies are more appropriate based on the prioritized barriers. Therefore, the uniqueness of this study lies in linking resource utilization, implementation barriers, and mitigation decisions within a single, structured CCSC decision-making framework. This framework supports the transformation of the cattle supply chain toward a more circular and sustainable system while strengthening the achievement of SDG 2 (Zero Hunger) through sustainable agriculture and SDG 8(Decent Work and Economic Growth) through value creation and economic growth.

Accordingly, this study aims to (1) analyze literature-derived opportunities for valorizing cattle waste and by-products and (2) develop an integrated decision framework for identifying and prioritizing CCSC implementation barriers and selecting appropriate mitigation strategies. The proposed framework combines waste-generation and valorization mapping with a two-stage MCDM structure in which FBWM is used for barrier prioritization and FTOPSIS for mitigation strategy evaluation and selection. This methodological sequence establishes a direct logical connection among the underlying problem of underutilized cattle waste and by-products, the barriers that hinder circular implementation, and the strategies required to address them. The principal contribution of this study is therefore an integrated conceptual decision framework that connects resource-recovery opportunities with implementation priorities and mitigation decisions across the cattle supply chain. Rather than providing empirically validated barrier rankings or mitigation strategies, the present literature-based study offers an analytical framework to guide subsequent stakeholder-based assessment and empirical application. In practical terms, the framework can support stakeholders in developing more systematic interventions to improve resource efficiency, generate added value from cattle by-products, reduce environmental burdens, and contribute to more circular and sustainable cattle supply chains.

MATERIALS AND METHODS

This study employs a conceptual approach based on a literature review to develop a CCSC framework that integrates the mapping of opportunities for cattle waste utilization with an analysis of barriers and the selection of mitigation strategies. All data used are secondary data obtained from relevant literature on CE, the utilization of cattle

waste and byproducts, and the application of MCDM in barrier analysis and strategy evaluation.

The framework was developed in two stages. The first stage focused on mapping the main activities of the cattle supply chain—from farming and slaughter to processing—to identify where waste and byproducts are generated and to link them to opportunities for utilization in value-added products. The waste and by-products analyzed included feces, urine, blood, wastewater, hides, offal, bones, as well as meat trimmings and fat [10]. The second stage focused on developing a framework for analyzing barriers to CCSC implementation, including identifying and classifying barriers, determining their weight and priority, formulating alternative mitigation strategies, and evaluating and selecting strategies. This structure forms a systematic decision-making process by linking priority barriers to the most relevant mitigation strategies. The resulting framework provides an analytical foundation for stakeholders to formulate policies and strategies to accelerate the transformation of the meat supply chain toward a more circular, efficient, and sustainable system.

RESULTS AND DISCUSSIONS

Results

The study produced two main outputs: a literature-based mapping of waste and by-product generation during cattle slaughtering and an integrated MCDM framework for CCSC barrier prioritization and mitigation strategy selection. Figure 1 shows that waste and by-products are generated across almost all stages of the slaughtering process, from livestock reception and washing to cutting and boning. The identified streams include feces, urine, blood, wastewater, hair, hooves, hides, heads, offal, digestive tract contents, bones, and meat and fat trimmings [10]. Data obtained from the literature provide quantitative evidence regarding several major waste streams and byproducts, as summarized in Table 1.

Table 1. Reported quantities of major organic waste and by-products generated during cattle processing [21]

Waste type	Amount generated
Manure, in feedlots	27 kg/day·animal (live weight 450 kg)
Manure, in meat processing	4–13 kg/t
Rumen waste	25–70 kg/t
Hair, hooves and horns	<50 g/hair from one animal hide; 8 kg/hooves per animal
Blood	15 L/head of cattle
Hides	28 kg/animal
Meat and Fat Waste	48 kg of meat meal per head, 52 kg of animal fat per head

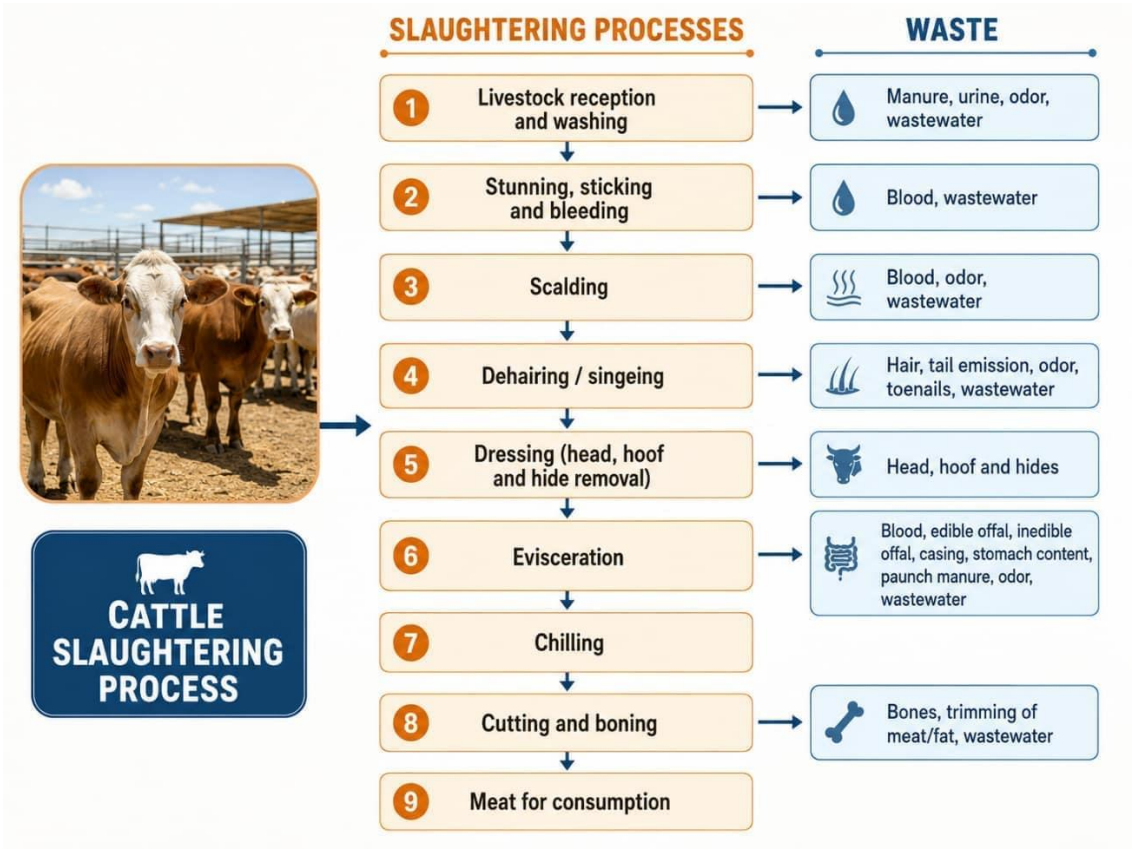

Figure 1. Flowchart of the slaughtering process and waste generation [10]

The second result of this study is the analytical structure used to connect CCSC barrier prioritization with mitigation strategy selection. Table 2 summarizes the MCDM methods according to the two analytical functions required in the proposed framework: weighting and prioritization, and evaluation and selection of alternatives. Methods such as AHP, ANP, BWM, and SWARA support the first function by generating factor weights and rankings [22-26], while the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and the Complex Proportional Assessment (COPRAS) support the second function by evaluating and ranking decision alternatives [23, 27, 28]. Based on these analytical functions, FBWM and FTOPSIS were selected to form the two-stage decision-making framework shown in Figure 2. In the first stage, relevant CCSC barriers are identified and classified; preferences are then determined to calculate weights and prioritize the barriers using FBWM. The resulting weights and rankings serve as input to the second stage, which involves formulating and evaluating alternative mitigation strategies, calculating each strategy's closeness to the ideal solution, and prioritizing them using FTOPSIS. The integration of these two stages establishes a clear analytical link between priority barriers and recommended mitigation strategies, ensuring that the selected strategies are directly targeted at the CCSC barriers with the highest priority levels.

Table 2. Classification of MCDM methods based on analytical function

Analysis Focus	Objectives	Methods	Outputs	References
Weighting and prioritization	Identifying the most important factors	AHP, ANP, BWM, SWARA.	Factor weights and rankings	[22-25] [26]
Evaluation and Selection of Alternatives	Selecting the best strategy from several alternatives	TOPSIS, PROMETHEE, COPRAS	Preference values and alternative rankings	[23, 27, 28]

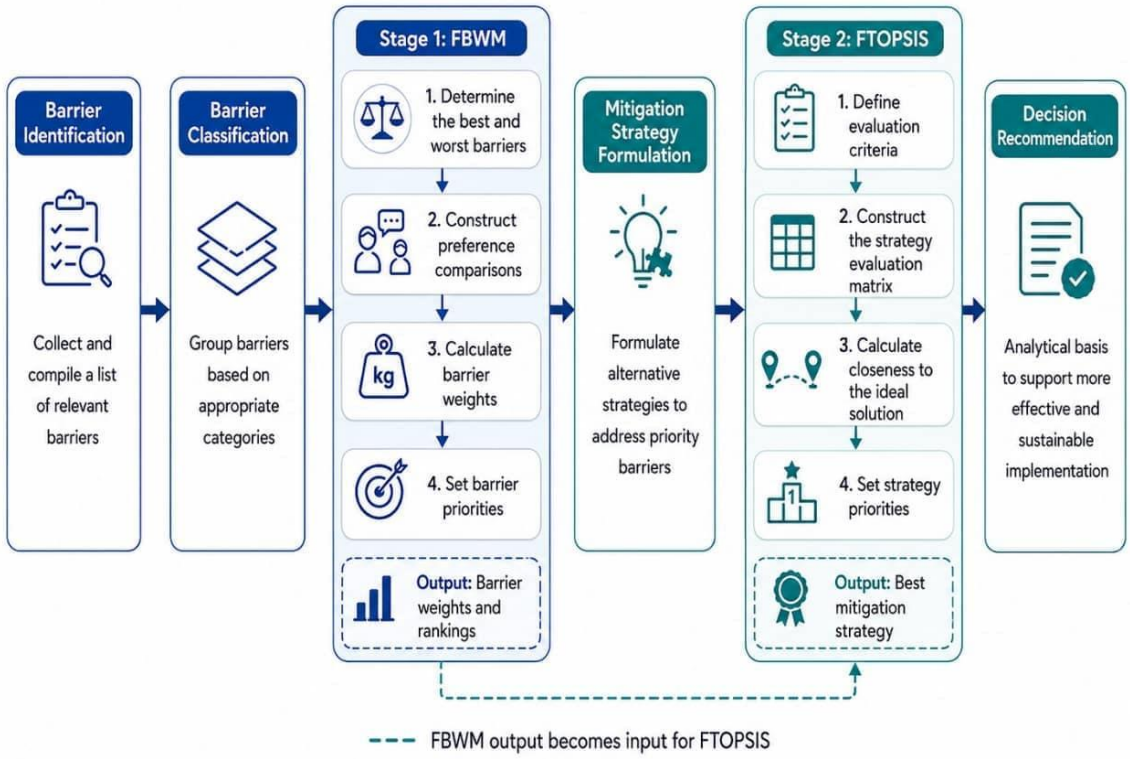

Figure 2. Framework for barrier analysis and mitigation strategy selection

Discussions

The mapping in Figure 1 shows that the cattle slaughtering process generates various types of waste and byproducts at nearly every stage. The identified waste includes feces, urine, blood, wastewater, hair, hooves, skin, heads, offal, digestive tract contents, bones, and meat trimmings and fat [10]. Based on Table 1, the reported figures indicate that significant quantities of waste streams and byproducts are generated. Meat and fat byproducts can yield approximately 48 kg of meat meal and 52 kg of animal fat per head. In addition, cattle manure in feedlots can reach 27 kg/head/day for cattle weighing about 450 kg, while rumen waste ranges from 25 to 70 kg/t. Blood production is about 15 L per head, while cattle hides and hooves yield about 28 kg and 8 kg per head. Among these byproducts, fat is a substance produced in relatively large quantities in the cattle farming sector [29]. This situation indicates that the slaughtering process not only produces meat as the primary product but also generates a stream of secondary materials that can be returned to the production system through the CE principle. Therefore, identifying the

points at which waste is generated is a crucial first step in determining valorization alternatives that align with each material's characteristics.

These various types of waste offer different opportunities for utilization. Blood and rumen contents from slaughterhouses can be used as raw materials for the production of biogas and biofertilizer [30]. Cattle urine, which is rich in urea, can be used as a natural fertilizer and growth promoter because it helps improve soil texture, provides micronutrients, and exhibits antimicrobial activity that supports soil fertility [31, 32]. Meanwhile, wastewater from slaughterhouses has a high organic load and a complex composition resulting from slaughtering, meat processing, washing, and sanitation activities, thus requiring effective treatment before disposal or reuse [33]. Bones also have economic value because they contain calcium, phosphorus, and high-quality protein in the form of collagen and gelatin [34]. Additionally, cattle hides can be sent to the tanning industry to be processed into tanned leather as a raw material for various products [35]. These uses demonstrate that cattle waste and byproducts can be transformed from an environmental burden into a resource that supports value creation within the CCSC.

Although opportunities for valorization exist, their implementation is still influenced by various barriers of varying importance. Therefore, the framework in Figure 2 positions FBWM as the initial stage for evaluating and prioritizing these barriers. Compared to conventional MCDM methods such as AHP and ANP, FBWM requires a more efficient comparison process and yields a higher level of assessment consistency [25, 36-38]. The use of fuzzy sets also allows FBWM to accommodate subjectivity and uncertainty in expert assessments when determining the relative importance of barriers [39]. The results of this stage consist of barrier weights and rankings, so that factors with the highest level of importance can be prioritized for addressing.

The prioritization of constraints serves as the basis for evaluating alternative mitigation strategies using FTOPSIS. This method evaluates each alternative based on a set of criteria and determines the best solution based on its distance from the positive ideal solution and its distance from the negative ideal solution [40]. Through this mechanism, strategies are not selected based on a single consideration but are evaluated simultaneously based on criteria relevant to the prioritized barriers. The integration of FBWM and FTOPSIS establishes a systematic decision-making process, as FBWM identifies the barriers most critical to address. At the same time, FTOPSIS determines which strategies are most appropriate for overcoming them. Thus, the developed framework directly links problem prioritization to the selection of mitigation actions and provides an analytical foundation to support stakeholders in achieving a more targeted, circular, and sustainable implementation of CCSC.

CONCLUSION

This study provides two main contributions to the development of a CCSC. First, the literature-based mapping shows that cattle slaughtering generates substantial and diverse waste and by-product streams across multiple processing stages, including manure, rumen, blood, hides, meat residues, and animal fat, with reported quantities indicating considerable potential for resource recovery. The reviewed literature further identifies potential valorization pathways, including biogas, biofertilizer, collagen, gelatin, and industrial raw materials. Second, the study proposes an integrated decision framework that sequentially connects waste valorization mapping, barrier prioritization, and mitigation strategy selection, thereby extending CCSC analysis from identifying resource-recovery opportunities to structuring the implementation barriers and actions

required to realize them. The novelty of the framework lies in linking these three decision stages within a single analytical structure, in which waste mapping identifies circular opportunities, barrier prioritization determines which implementation barriers require greater attention, and mitigation strategy selection directs appropriate responses to those priority barriers. In practical terms, the framework can assist slaughterhouse operators, supply-chain actors, and policymakers in systematically identifying valuable waste streams and organizing subsequent barrier and mitigation assessments to support resource efficiency, waste reduction, and value creation. A limitation of this study is its reliance on a conceptual, literature-based approach; consequently, the framework has not yet been validated through empirical data or stakeholder assessments. Future research should test the framework by involving actors in the meat supply chain, apply the FBWM–FTOPSIS approach using actual data, and conduct sensitivity analyses to evaluate the stability of barrier priorities and mitigation strategies under various CCSC implementation conditions.

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