



A New Hybrid Fuzzy Decision Model for Barrier Identification and Strategy Prioritization in Circular Rice Supply Chains: A Case Study in Indonesia

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ABSTRACT

This study aims to identify barriers to implementing a circular rice supply chain in Indonesia and to prioritize strategies for overcoming them. Data were collected from seven experts representing academia, industry, farmer cooperatives, and government agencies. A hybrid fuzzy framework was applied, combining the Fuzzy Delphi method to validate barriers, the Fuzzy Best-Worst Method to assign weights, and the Fuzzy Complex Proportional Assessment to rank solutions. Results reveal that the most critical barriers lie in the Economy and Investment dimension, particularly high financial costs and risks, lack of incentives, short-term economic orientation, capital-intensive spending, and low raw material prices. Priority strategies include cross-sector partnerships and fiscal incentives, supported by logistics hubs and circular literacy training. The study concludes that successful adoption requires not only technology but also enabling regulations, economic incentives, and managerial change. These findings provide actionable guidance for policymakers and supply chain managers to build sustainable, resilient food systems.

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1. INTRODUCTION

The development of Circular Economy (CE) values is considered a strategic response to the global sustainability situation in many sectors [1], including agriculture. CE focuses on reducing, reusing, and recycling waste, as well as regenerating resources to increase efficiency and reduce environmental harm [2]. Moreover, CE is not only about conserving resources but also enhancing system productivity by extending product life cycles through reuse, remanufacturing, repair, and preserving material quality [3-5]. CE adoption is particularly important in the Indonesian rice supply chain, which faces large postharvest losses, inefficient distribution systems, and significant environmental degradation due to conventional farming practices. Like other agrarian countries with high rice consumption, Indonesia needs its rice production and distribution system to operate efficiently, resiliently, and sustainably. Extensive application of CE across crop production, harvesting, processing, transportation, consumption, and postharvest waste management is vital for enhancing national food security and mitigating ecological destruction [6]. In addition, CE represents an effective strategy to save resources, reduce ecological pressure, and improve efficiency in the mainstream agricultural industry [7,8]. Therefore, advancing a sustainable rice supply chain through circular economy practices provides opportunities for technological innovation, inter-industry collaboration, and value co-creation [9]. Applying CE principles to the rice supply chain is thus a strategic imperative for ensuring food security, optimizing system performance, and achieving environmental sustainability.

An accurate understanding of the barriers is essential for achieving a successful and sustainable circular supply chain (CSC) [10]. In implementing CSC practices, barriers can arise both within the organization and from external factors. If these barriers are not systematically identified and addressed, they can hinder the transition from a linear to a circular supply chain [11]. Therefore, identifying obstacles that are specific to CSC is crucial to ensure that research reflects the real dynamics of supply chains. A comprehensive analysis of these barriers is necessary to guarantee that the shift from linear to circular systems is feasible and that no hidden obstacles remain [12]. It is also important to standardize systems for permeate recovery from food processing wastewaters in CSCs, following the principles of reduce, reuse, and recycle (3R) [13]. Such assessments should evaluate not only the relevance of each indicator but also prioritize barriers across multiple factors using a structured, data-driven approach. This methodology brings issues to light and enables their prioritization, allowing appropriate remedies to be developed. Furthermore, selecting strategies that address the identified barriers is vital to ensure CSC initiatives remain adaptive to evolving challenges, maintain effectiveness in practice, and contribute to the development of competitive and sustainable supply chain systems. Previous research has shown that Multi-Criteria Decision Making (MCDM) approaches have been widely applied to evaluate barriers and prioritize strategies for implementing CSC across various industries. For example, the combination of Best Worst Method (BWM), Interpretive Structural Modeling (ISM), and MICMAC has been used to weight barriers in the electronics manufacturing sector [14]. The Rough-DEMATEL method has been applied to identify and map barriers and strategies in the food sector [15], while Fuzzy BWM combined with Fuzzy DEMATEL has been employed in the polyvinyl chloride (PVC) manufacturing industry [16]. Similarly, fuzzy-AHP has been applied to assess and weight barriers in the plastics industry [17], and BWM has been used for barrier prioritization in general manufacturing contexts [18]. Other studies have adopted the Robust-Hybrid BWM (R-HBWM) to evaluate barriers in manufacturing industries [19] and integrated Fuzzy Delphi with BWM for barrier relevance assessment and weighting [20]. Additionally, DEMATEL has

been applied in the textile sector [21], DEMATEL combined with AHP in company-level studies [22], and Grey Delphi together with Grey BWM in the biscuit industry. Further applications include ISM-MICMAC for manufacturing [23], Fuzzy DEMATEL for the food sector [24], Fuzzy ANP in manufacturing [25], Pythagorean fuzzy AHP-DEMATEL in the automotive plastics industry [26], and Grey DEMATEL for broader manufacturing applications [27]. Although these studies provide valuable insights into the evaluation and weighting of barriers, most focus primarily on methodological implementation. They generally emphasize identifying and prioritizing barriers without linking them systematically to strategies that are context-specific and actionable. As a result, the findings offer limited guidance for policymakers and are less applicable to sectors like the rice commodity chain, where systemic challenges and societal factors demand more comprehensive and realistic solutions.

Despite the widespread use of MCDM methods in the literature, significant gaps remain in research on the implementation of CSC. Previous studies have primarily focused on assessing and ranking barriers, with limited attention given to linking context-specific challenges to systematically formulated and prioritized strategies. Consequently, much of the research remains descriptive, offering little in the way of tangible, actionable solutions to facilitate the practical transition from linear to circular supply chains. This limitation reduces the practical value of their findings, as decision-makers cannot readily adopt these strategic directions. Furthermore, no research to date has specifically identified the barriers and enablers for implementing CSC in rice supply chains, a sector with unique characteristics, including dependence on smallholder farmers, seasonality, and widespread supply and distribution inefficiencies typical of agrarian economies such as Indonesia. The lack of research on this critical sector creates a notable gap in developing a practical and measurable decision-making framework for sustainable staple food systems. Therefore, there is a scarcity of literature that combines barrier identification, prioritization, and strategy development specifically for the rice supply chain. Addressing this gap is essential to provide robust methodological and practical guidance that supports the systemic transition toward circularity in one of the most strategic agricultural sectors.

This paper aims to contribute by proposing a holistic framework for assessing the relevance and priority of barriers, as well as for prioritizing strategies to mitigate these barriers in adopting the circular rice supply chain. The model is developed using an MCDM approach, integrating the Fuzzy Delphi method to explore identified barriers and strategies, the Fuzzy BWM to determine the relative importance of barriers, and the Fuzzy Complex Proportional Assessment (COPRAS) to rank strategies based on their effectiveness and feasibility.

From a scholarly perspective, this research advances methodological development in circular supply chain assessment by introducing a hybrid fuzzy MCDM model applied to a strategic food sector (rice), which has received limited attention in prior studies. This comprehensive model of barrier identification and prioritization improves upon previous work that treated barriers or uncertainty in isolation, without systematically linking them to strategies. On the applied side, the study provides evidence-based strategic guidance for policymakers, supply chain managers, and agribusiness practitioners to identify the most critical obstacles to circular adoption and implement prioritized strategies for transitioning to sustainable rice supply chains.

By applying Fuzzy Delphi, experts can express their opinions objectively to reach consensus [28]. This method gathers expert judgments using fuzzy numbers to determine the relevance level of each activity [29,30]. The use of Fuzzy BWM in qualitative decision-making provides more accurate results and better reflects real-world conditions [31]. Compared to other MCDM techniques such as AHP and ANP, BWM is relatively easier to implement [32] and is

more consistent than AHP [33,34]. The COPRAS method, in contrast, is an effective and straightforward technique for addressing MCDM problems [35]. COPRAS offers several key advantages: it is simple to apply and understand, it considers both ideal and anti-ideal solutions simultaneously, and it enables decision-making within a relatively short time frame [36]. Applying the Fuzzy COPRAS method to strategy ranking provides specific and practical recommendations that can facilitate circular practices, such as recycling agricultural waste, optimizing logistics, or mitigating carbon emissions. Overall, this framework creates an enabling environment for adaptive decision-making based on local conditions and supports the transition of rice supply chains toward more efficient, sustainable, and competitive systems.

This paper is organized as follows. Section 2 presents a literature review covering circular supply chains and multi-criteria decision-making approaches. Section 3 introduces the proposed hybrid fuzzy decision-making framework and details the procedural steps followed in this study. Section 4 describes the data collection process and the case study context, specifically the rice supply chain in Indonesia. Section 5 presents and analyzes the results, including the weighting of barriers and the prioritization of strategies. Section 6 discusses the theoretical and managerial implications of the findings. Finally, Section 7 concludes the paper by summarizing the main findings, highlighting limitations, and suggesting directions for future research.

2. LITERATURE REVIEW

The adoption of MCDM approaches has emerged as a prominent method for evaluating barriers and identifying strategies for implementing CSC. Previous research has explored various methodological combinations to address the complexity of CSC adoption across different industrial sectors. For example, several researchers [14] applied a hybrid BWM-ISM-MICMAC approach to assess and prioritize barriers in the electronics manufacturing sector, while several researchers [15] employed Rough-DEMATEL to analyze barriers and their interdependencies in the food industry. Several researchers [16] further advanced this line of research by integrating Fuzzy BWM with Fuzzy DEMATEL in the copper and PVC manufacturing sector, demonstrating the effectiveness of fuzzy-based methods in handling uncertainty in expert judgments. In the plastics and broader manufacturing industries, studies have also used fuzzy-AHP [17], BWM [18], and R-HBWM [19] to prioritize barriers, providing valuable methodological insights for barrier evaluation.

Beyond these contributions, subsequent research has continued to refine weighting techniques but has often remained focused solely on barrier evaluation. For instance, ISM–MICMAC was employed to prioritize barriers in manufacturing applications [23], Fuzzy DEMATEL was adopted to analyze barriers in the food sector [24], Fuzzy ANP was applied in manufacturing [25], and Pythagorean fuzzy AHP–DEMATEL was introduced in the automotive plastics industry [26]. Similarly, Grey DEMATEL was used for broader manufacturing applications [27]. While these approaches enhanced methodological rigor in barrier prioritization, they did not extend the analysis toward actionable strategies. The combination of relevance assessment with weighting through Fuzzy Delphi–BWM and Grey Delphi–GG-BWM was proposed to advance barrier evaluation [10]; however, even these integrative methods remained confined to barrier assessment without systematically linking findings to strategy development.

From the literature, two major observations can be made. First, most models effectively assign priorities to barriers across various industrial sectors, providing methodological advancements in MCDM. Second, despite these contributions, most studies fail to bridge the

gap between barrier identification and the formulation of context-specific, prioritized strategies, limiting the practical applicability of their findings. This synthesis is summarized in **Table 1**, which reports the methods, types of evaluation (relevance, weighting, strategy formulation), and the industrial sectors studied. While some previous studies demonstrate notable methodological strengths, none integrate all three elements barrier identification, weighting, and strategy prioritization within a single, coherent framework.

Of particular importance is the limited attention given by researchers to circular rice supply chains. The rice market faces several unique challenges, including reliance on smallholder farmers, high seasonality, and complex distribution networks in agrarian societies. These characteristics distinguish it from industrial manufacturing sectors and necessitate tailored approaches for barrier assessment and strategy prioritization. This paper addresses this gap by employing a hybrid methodology that combines Fuzzy Delphi, Fuzzy BWM, and Fuzzy COPRAS. This approach not only validates and prioritizes the identified barriers but also systematically links them to actionable strategies, providing an integrated decision-support tool to promote the adoption of circular practices in the rice supply chain.

Table 1. Literature review related to the use of MCDM methods for Circular Supply Chain adoption.

Relevance Assessment	Weighting of barriers	Strategy Determination	MCDM Method	Sector	Ref
-	V	-	BWM-ISM-MICMAC	Electronics Manufacturing	[14]
-	V	-	Rough-DEMATEL	Food	[15]
-	V	-	Fuzzy BWM-Fuzzy DEMATEL	Copper and polyvinyl chloride (PVC) Manufacturing	[16]
-	V	-	fuzzy-AHP	Plastic Industry	[17]
-	V	-	BWM	Manufacturing	[18]
-	V	-	R-HBWM	Manufacturing	[19]
V	V	-	Fuzzy Delphi-BWM	-	[20]
	V	-	DEMATEL	Textile	[21]
	V	-	DEMATEL & AHP	Companies	[22]
-	V	-	ISM- MICMAC	Manufacturing	[23]
-	V	-	Fuzzy DEMATEL	Food	[24]
-	V	-	Fuzzy ANP	Manufacturing	[25]
-	V	-	Pythagoras fuzzy AHP-DEMATEL	Automotive plastic industry	[26]
-	V	-	Grey DEMATEL	Manufacturing	[27]
V	V	V	Fuzzy Delphi, Fuzzy BWM, and Fuzzy COPRAS	Rice	This reaserch

3. RESULTS AND DISCUSSION

3.1. Proposed Hybrid Fuzzy Decision Model

Given the challenges of implementing circular rice supply chains, this study develops a three-stage hybrid fuzzy methodology combining Fuzzy Delphi, Fuzzy BWM, and Fuzzy COPRAS (see **Figure 1**). The process begins with Fuzzy Delphi to confirm relevant barriers through expert consensus, retaining only the most significant barriers for further analysis. Next, the validated barriers are weighted using Fuzzy BWM, which assesses their relative

importance by comparing the best and worst barriers within each category. Finally, Fuzzy COPRAS links the weighted barriers to potential strategies, enabling a systematic comparison of alternatives in terms of feasibility and effectiveness. This sequential approach ensures that the proposed framework not only identifies and prioritizes critical barriers but also generates actionable strategies to facilitate the transition of rice supply chains toward a circular model.

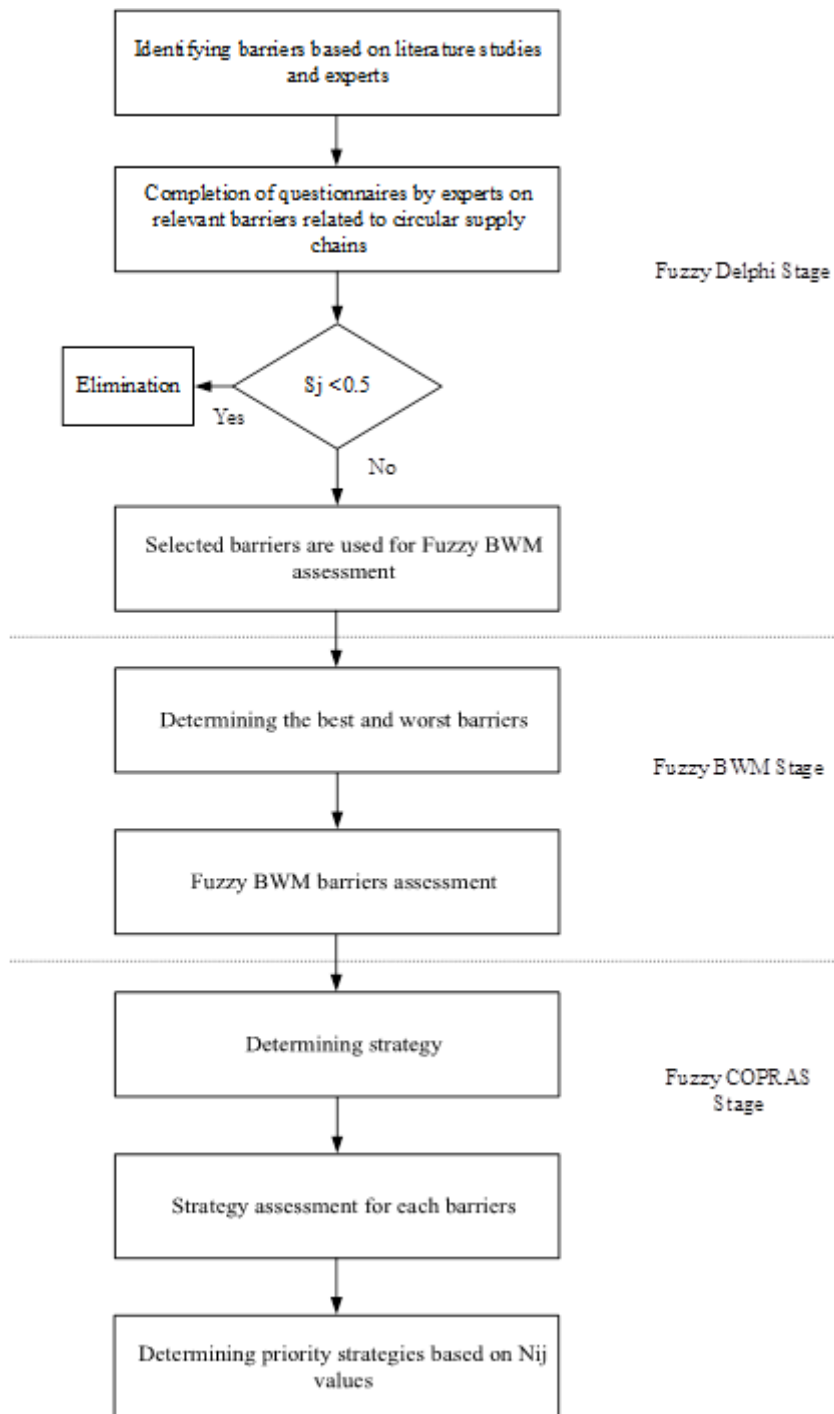


Figure 1. Framework Proposed Hybrid Fuzzy Decision Model.

The first phase of the proposed framework focuses on identifying barriers to circular supply chain adoption. This process began with an extensive review of the literature, examining previous studies on the implementation of circular economy and supply chain practices, particularly those addressing technological, economic, organizational, regulatory, and social

dimensions. The review generated a comprehensive list of potential barriers, reflecting the complexity of transitioning from linear to circular production models. Domain experts from academia, industry, farmer cooperatives, and government agencies were then consulted to refine and validate the barrier set. This combination of literature-based evidence and expert input ensured that the identified barriers were both theoretically sound and practically relevant, providing a robust foundation for the subsequent evaluation using a fuzzy multi-criteria decision-making approach.

The relevance of barriers identified through literature review and expert consultations was validated using the Fuzzy Delphi Method. In the first phase, a systematic review and preliminary discussions with experts produced a list of potential barriers for assessment. The relative priority of each barrier was evaluated by a panel of experts from academia, farmer cooperatives, industry, and government institutions using linguistic variables ranging from Very Low to Very High, as defined in **Table 2**. Then the linguistic values were transformed into Triangular Fuzzy Numbers (TFN), denoted by $\tilde{a}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where i is the expert and j is the barrier. Modeling linguistic judgments is given in Equation (1). The overall fuzzy weight of each barrier W_j was obtained by taking the minimum lower bound, the average middle value, and the maximum upper bound among experts using Equations (2) and (3). Defuzzification was conducted using the Center of Gravity (COG) method to generate crisp values for each barrier. This process transformed the fuzzy weight into a single representative value S_j , which was calculated as shown in Equation (4) [37].

$$\tilde{a}_{ij} = (a_{ij}, b_{ij}, c_{ij}), i = 1, 2, \dots, n; j = 1, 2, \dots, m \quad (1)$$

$$W_j = (a_j, b_j, c_j), j = 1, 2, \dots, m. \quad (2)$$

$$a_j = \text{Min}_i (a_{ij}), b_j = \frac{1}{n} \sum_{i=1}^n (b_{ij}), c_j = \text{Max}_i (c_{ij}) \quad (3)$$

$$S_j = \frac{a_j + b_j + c_j}{3}, j = 1, 2, \dots, m. \quad (4)$$

Barriers with crisp values greater than or equal to the threshold ($S_j \geq 0.5$) were retained for further analysis, while those below this cut-off point were eliminated. This procedure ensured that only significant and consensus-based barriers advanced to the next stage of the hybrid framework.

Table 2. Linguistic variables for assessing the relevance of barriers

Relevance Level	Code	Triangular Fuzzy Number Scale
Very High	VH	(0.75, 1, 1)
High	H	(0.5, 0.75, 1)
Medium	M	(0.25, 0.5, 0.75)
Low	L	(0, 0.25, 0.5)
Very Low	VL	(0, 0, 0.25)

The second stage of the proposed framework employs the Fuzzy Best Worst Method (Fuzzy BWM) to determine the relative importance of the validated barriers. This stage begins with identifying the best and worst barriers within each of the eight dimensions technology, technical, regulation and policy, economy and investment, organization and management, operations and supply chain, market and competition, and social and awareness through focus group discussions with experts. Each expert then performs pairwise comparisons between the best barrier and all other barriers, as well as between all other barriers and the worst barrier, using the linguistic scales provided in **Table 3** [38]. These linguistic judgments

are subsequently converted into Triangular Fuzzy Numbers (TFNs), forming two comparison vectors: the fuzzy best-to-others vector, as shown in Equation (5), and the fuzzy others-to-worst vector, as shown in Equation (6).

$$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{Bn}) \tag{5}$$

$$\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, \dots, \tilde{a}_{nW}) \tag{6}$$

Table 3. Linguistic Variables Fuzzy BWM

Linguistic variables	Code	Membership Function
Equally Important	EI	(1, 1, 1)
Weakly Important	WI	(2/3, 1, 3/2)
Fairly Important	FI	(3/2, 2, 5/2)
Very Important	VI	(5/2, 3, 7/2)
Absolutely Important	AI	(7/2, 4, 9/2)

The optimal fuzzy weights are then obtained by solving a nonlinear min–max optimization model in Equation (7), subject to normalization and non-negativity constraints formulated in Equation (8). The weights are expressed as TFNs, $\hat{W}_j = (l_j^w, m_j^w, u_j^w)$, where l_j^w, m_j^w, u_j^w represent the lower, middle, and upper bounds of the fuzzy weight for the barrier j .

$$\text{Min } \xi \left\{ \left| \frac{\hat{W}_B}{\hat{W}_j} - \tilde{a}_{bj} \right|, \left| \frac{\hat{W}_j}{\hat{W}_W} - \tilde{a}_{jw} \right| \right\} \tag{7}$$

$$\text{s.t. } \begin{cases} \sum_{j=1}^n R(\hat{W}_j) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ l_j^w \geq 0 \\ j = 1, 2, \dots, n \end{cases} \tag{8}$$

The optimal weight is determined using an optimization model that minimizes the maximum deviation between the fuzzy weight ratio and the expert assessment. The objective function is shown in Equation (7), while the detailed form with constraints is given in Equation (9) with $k^*, k^*, k^* = \bar{\xi}$.

$$\text{Min } \bar{\xi} \begin{cases} \left| \frac{l_b^w, m_b^w, u_b^w}{l_j^w, m_j^w, u_j^w} - (l_{bj}, m_{bj}, u_{bj}) \right| \leq (k^*, k^*, k^*) \\ \left| \frac{l_j^w, m_j^w, u_j^w}{l_w^w, m_w^w, u_w^w} - (l_{jw}, m_{jw}, u_{jw}) \right| \leq (k^*, k^*, k^*) \\ \sum_{j=1}^n R(\hat{W}_j) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ l_j^w \geq 0 \\ j = 1, 2, \dots, n \end{cases} \tag{9}$$

The optimal fuzzy weights are then defuzzified using the fuzzy rating function using Equation (10). Consistency of assessment is calculated using the Consistency Ratio (CR) (Equation (11)), where ξ is compared with the Consistency Index (CI) that has been determined based on the linguistic scale shown in **Table 4**.

$$R(\hat{W}_j^*) = \frac{l_j^* + 4m_j^* + u_j^*}{6} \tag{10}$$

$$CR = \frac{\bar{\xi}^*}{CI} \tag{11}$$

Table 4. Consistency Index Fuzzy BWM.

Linguistic Terms	(EI)	(WI)	(FI)	(VI)	(AI)
\tilde{a}_{bw}	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(7/2, 4, 9/2)
CI	3.00	3.80	5.29	6.69	8.04

The final stage of the research framework applies Fuzzy Complex Proportional Assessment (Fuzzy COPRAS) to prioritize strategies for overcoming barriers to the adoption of a circular rice supply chain. This method was selected for its ability to incorporate the uncertainty of expert assessments through fuzzy representation and to generate measurable, transparent strategy rankings. The process begins by establishing the linguistic scale used by experts to evaluate the effectiveness of strategies in addressing the previously identified barriers. The linguistic scale, ranging from Very Low to Very High, is then converted into Triangular Fuzzy Numbers (TFNs), as detailed in **Table 5**. For instance, a Medium rating is represented by (0.3, 0.5, 0.7), while a Very High rating is represented by (0.8, 1.0, 1.0).

Expert assessments were aggregated into a fuzzy decision matrix \tilde{D} (in Equation 12), where each element $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ denotes the fuzzy evaluation of strategy i with respect to the barrier j . The weights of the criteria, obtained from the Fuzzy BWM stage, are expressed as $\tilde{W} = [w_1, w_2, \dots, w_n]$.

Table 5. Linguistic scale and Triangular Fuzzy number assessment of strategies using COPRAS

Linguistic scale	Code	Triangular Fuzzy number
Very low	VL	(0, 0, 0.2)
Low	L	(0, 0.2, 0.4)
Medium	M	(0.3, 0.5, 0.7)
High	H	(0.6, 0.8, 1)
Very high	VH	(0.8, 1, 1)

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \tag{12}$$

The fuzzy decision matrix was normalized to ensure comparability across criteria. Normalization was carried out by dividing each element by the total value of its respective criterion, as shown in Equation (13).

$$\bar{x}_{ij} = \frac{\tilde{x}_{ij}}{\sum_{j=1}^n \tilde{x}_{ij}}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \tag{13}$$

Furthermore, the normalized matrix was multiplied by the corresponding criterion weights to form the weighted normalized decision matrix \hat{X} , as shown in Equation (14).

$$\hat{X} = \begin{bmatrix} \hat{x}_{11} & \hat{x}_{12} & \dots & \hat{x}_{1n} \\ \hat{x}_{21} & \hat{x}_{22} & \dots & \hat{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{x}_{m1} & \hat{x}_{m2} & \dots & \hat{x}_{mn} \end{bmatrix} \tag{14}$$

Next, the useful weighted normalized criterion values were calculated for each alternative strategy by distinguishing between benefit-type obstacles (where higher values are preferable) and cost-type obstacles (where lower values are preferable), as formulated in Equations (15) and (16). The minimum value among the cost criteria was used as the baseline for relative comparison, as expressed in Equation (17).

$$\tilde{P}_i = \sum_{j=1}^k \hat{x}_{ij}, i = 1, 2, \dots, m \quad (15)$$

$$\tilde{R}_i = \sum_{j=k+1}^n \hat{x}_{ij}, i = 1, 2, \dots, m \quad (16)$$

$$\tilde{R}_{min} = \min \tilde{R}_i, i = 1, 2, \dots, m \quad (17)$$

Furthermore, the relative weight of each strategy (Q_i) was computed by combining its benefit score \tilde{P}_i and adjusted cost score \tilde{R}_i , normalized by the minimum cost criterion, as described in Equation (18). The maximum relative weight (Q_{max}) was then identified across all alternative strategies, as shown in Equation (19).

$$Q_i = \tilde{P}_i + \frac{\tilde{R}_{min} \sum_{i=1}^n \tilde{R}_i}{\tilde{R}_i \sum_{i=1}^n \frac{\tilde{R}_{min}}{\tilde{R}_i}}; i = 1, 2, \dots, m \quad (18)$$

$$Q_{max} = \max (Q_i) \forall i = 1, 2, \dots, m \quad (19)$$

Finally, the utility degree of each strategy (N_i) was obtained by dividing its relative weight by the maximum value and expressing it as a percentage, as indicated in Equation (20).

$$N_i = \frac{Q_i}{Q_{max}} \times 100 \quad (20)$$

The final result of the Fuzzy COPRAS process is the effectiveness degree N_i , which indicates the relative effectiveness of each alternative strategy as a percentage of the best performing strategy. A higher N_i value signifies a greater ability of the strategy to overcome barriers in the circular rice supply chain. Consequently, the strategy with the highest degree of utility is selected as the most effective and critical strategy, while the remaining strategies are ranked to guide policymakers, supply chain managers, and other stakeholders.

3.2. Data and Case Study

This study collected primary data through in-depth interviews and expert assessments during the Fuzzy Delphi stage, as well as through focus group discussions (FGDs) for the Fuzzy BWM and Fuzzy COPRAS stages. A total of seven experts were purposively selected to ensure adequate representation across key dimensions, including technology, technical, regulation and policy, economy and investment, organization and management, supply chain operations, market and competition, and social and awareness aspects. The panel included academics, rice milling industry practitioners, representatives of farmer cooperatives, and officials from local government agencies responsible for food management and environmental regulation.

Experts were asked to evaluate the relevance of 49 barriers identified from the literature, as presented in **Table 6**. Each expert completed a structured questionnaire using linguistic variables ranging from Very Low (VL) to Very High (VH). These linguistic judgments were then converted into Triangular Fuzzy Numbers (TFNs) to facilitate fuzzy-based measurement. The significance value (S_j) for each barrier was calculated to determine whether it should be

retained or eliminated. As shown in **Table 8**, 44 barriers were confirmed as relevant with $S_j \geq 0.5$, while five barriers were removed for scoring below the threshold.

Following this stage, pairwise comparisons were conducted among barriers within each dimension to identify the best and worst barriers. These assessments produced evaluation matrices, presented in **Tables 9–17**, covering the overall barrier dimension (**Table 9**), technology (**Table 10**), technical (**Table 11**), regulation and policy (**Table 12**), economy and investment (**Table 13**), organization and management (**Table 14**), supply chain operations (**Table 15**), market and competition (**Table 16**), and social and awareness (**Table 17**). All expert evaluations were converted into fuzzy numbers following the established procedure, resulting in fuzzy weights for each barrier. These weights were then analyzed using the Fuzzy BWM to calculate priority weights, which subsequently served as inputs for the Fuzzy COPRAS method to rank the strategies.

The set of alternative strategies for addressing the identified barriers is presented in **Table 7**, while **Table 18** provides expert evaluations of these strategies against each barrier. By following this structured process, the study ensured replicability, involving the same number of experts, utilizing questionnaires based on fuzzy linguistic scales, and strictly adhering to the procedures for conversion, normalization, and weighting. This robust design provides a solid empirical foundation for generating reliable strategy rankings to support the transition toward a circular rice supply chain.

Table 6. Barriers to circular supply chain adoption.

Dimensions	Barriers	Barrier Code	Type	Ref
Technology (T)	Limited eco-friendly technology and innovation for waste processing (rice husk, wastewater, etc.)	B1	Benefit	[14-19]
	Security issues	B2	Benefit	[15,19]
	Complexity in recycling rice husk waste, washing water, and bran	B3	Benefit	[14]
	Environmental productivity of technological processes	B4	Benefit	[19]
	Lack of product recycling related to limited circular reuse efforts, such as husk-to-biomass energy or animal feed	B5	Benefit	[10,19]
Technical (Tec)	Lack of operational models and technical methods for the Circular Supply Chain	B6	Benefit	[17]
	Inadequate collection centers and recycling facilities, including the absence of husk banks or bran hubs	B7	Benefit	[17]
	Lack of human resources and technical expertise in implementing Circular Supply Chains, including many farmers and business actors unfamiliar with circular practices	B8	Benefit	[10, 14, 15, 16, 17]
	Lack of information systems to track recycled materials into products	B9	Benefit	[17,19]
	Lack of circular design and innovative rice packaging to reduce food waste	B10	Benefit	[10]
Regulations and Policies (RP)	Lack of government support and incentives (regulatory and financial)	B11	Benefit	[10, 14, 16, 19]
	Absence of regulatory frameworks, standards, and technical guidelines	B12	Benefit	[15,16]
	Weak enforcement of environmental protection rules and regulations	B13	Benefit	[10,17,18]

Table 6 (continue). Barriers to circular supply chain adoption.

Dimensions	Barriers	Barrier Code	Type	Ref
Economy and Investment (EI)	Lack of global standards to measure CSCM performance	B14	Benefit	[17-19]
	Weak government regulations related to Intellectual Property Rights (IPR) for circular products	B15	Benefit	[18]
	High financial costs and risks in investment and operations	B16	Benefit	[10,14-18]
	Short-term perspective on economic benefits	B17	Benefit	[17]
	Higher prices of recycled products	B18	Benefit	[17]
	Capital expenditure is prioritized over operational expenditure	B19	Benefit	[18]
	The low price of virgin raw materials makes circular processes economically unattractive.	B20	Benefit	[18]
Organization and Management (OM)	Lack of stakeholder support and awareness	B21	Benefit	[10,14-19]
	Resistance from legacy business models	B22	Benefit	[15-17]
	Absence of a proper long-term vision for sustainability and scalability	B23	Benefit	[14]
	Low industry participation	B24	Benefit	[15]
	Absence of standardized systems for performance evaluation	B25	Benefit	[16]
	Risk aversion	B26	Benefit	[16]
	Lack of flexibility and coordination across departments	B27	Benefit	[17]
Operations and Supply Chain (OSC)	Inadequate environmental programs	B28	Benefit	[18]
	Lack of reliable information	B29	Benefit	[18]
	Complex supply chain networks	B30	Benefit	[14,15,18]
	Lack of accurate estimates of waste quantity and type	B31	Benefit	[14]
	Incompatible infrastructure and operations	B32	Benefit	[14]
	Absence of efficient waste management systems	B33	Benefit	[14]
	High transportation costs	B34	Benefit	[18]
Market and Competition (MC)	Increasing uncertainty	B35	Benefit	[19]
	Limited quality partners within the supply chain	B36	Benefit	[10,15,16,18,19]
	Organizational culture is dependent on traditional practices	B37	Benefit	[19]
	Limited training and development on circular technology and waste management among stakeholders	B38	Benefit	[17]
	Low acceptance and negative consumer perception of circular products	B39	Benefit	[10, 16-19]
	Lack of collaboration and information exchange among supply chain actors (e.g., fertilizers or feed from waste perceived as inferior)	B40	Benefit	[10,17,19]
	Absence of integrated reverse logistics networks for packaging, husks, used sacks, etc.	B41	Benefit	[10,17]
Brand image	B42	Benefit	[19]	

Table 6 (continue). Barriers to circular supply chain adoption.

Dimensions	Barriers	Barrier Code	Type	Ref
Social and Awareness (SA)	Lack of standardization for product modernization	B43	Benefit	[19]
	Limited access to product recycling	B44	Benefit	[19]
	Vulnerability to trend-driven models	B45	Benefit	[19]
	Product complexity and customization	B46	Benefit	[19]
	Lack of public knowledge of circular technologies	B47	Benefit	[14,18]
	Weak social and cultural pressure toward the Circular Economy	B48	Benefit	[16]
	Unsupportive consumer behavior (unwilling to pay, unsustainable usage of products)	B49	Benefit	[19]

Table 7. Strategies to overcome barriers.

Code	Strategy Description
S1	The government should provide green subsidies or tax incentive schemes for farmers, rice milling industries, and businesses that adopt environmentally friendly technologies and circular practices.
S2	Establish partnership platforms between the government, farmer cooperatives, the private sector, and financial institutions to share investment costs for circular technologies.
S3	Develop a digital traceability system based on IoT or blockchain to monitor the flow of rice, husks, and post-production waste.
S4	The government should establish national standards for the circular rice supply chain (e.g., Indonesian National Standards for circular products), including product certification for husk waste processing and carbon emission standards.
S5	Organize tiered training programs for farmers, rice mills, and food SMEs on circular practices (waste reuse, biomass energy, logistics efficiency). On the consumer side, circular rice literacy campaigns can raise awareness of the environmental and health benefits of circular products.
S6	Promote research and development of eco-friendly rice packaging designs (biodegradable, reusable) and market rice products with eco-labels or halal-green labels.
S7	Establish circular logistics hubs in rice production centers to integrate rice distribution and husk/paddy waste management. Through reverse logistics schemes, waste can be efficiently collected and recycled into biomass energy, fertilizer, or industrial raw materials.

Table 8. Results of Barrier Relevance Assessment.

Code	Expert							S_j	Decision
	1	2	3	4	5	6	7		
B1	H	VH	H	M	H	VH	H	0.672	Relevant
B2	L	VL	M	L	VL	L	L	0.250	Not Relevant
B3	H	H	M	VH	H	H	M	0.648	Relevant
B4	L	L	M	L	VL	M	L	0.250	Not Relevant
B5	H	VH	H	M	VH	H	H	0.672	Relevant
B6	H	H	M	VH	H	H	M	0.648	Relevant
B7	H	VH	H	H	M	H	VH	0.672	Relevant
B8	VH	H	H	M	VH	H	H	0.672	Relevant
B9	H	M	H	VH	H	H	H	0.662	Relevant
B10	H	VH	H	H	H	M	VH	0.672	Relevant
B11	VH	H	VH	H	H	M	H	0.672	Relevant
B12	H	VH	H	VH	H	VH	H	0.782	Relevant
B13	VH	H	H	H	VH	H	H	0.771	Relevant
B14	H	H	M	VH	H	H	H	0.662	Relevant

Table 8 (continue). Results of Barrier Relevance Assessment.

Code	Expert							S_j	Decision
	1	2	3	4	5	6	7		
B15	L	L	VL	M	L	VL	L	0.250	Not Relevant
B16	VH	H	VH	H	VH	H	H	0.782	Relevant
B17	H	VH	H	H	M	H	H	0.662	Relevant
B18	H	H	M	H	VH	H	H	0.662	Relevant
B19	H	H	VH	H	H	M	VH	0.672	Relevant
B20	H	VH	H	H	H	H	VH	0.771	Relevant
B21	H	VH	H	H	H	VH	H	0.771	Relevant
B22	H	H	VH	H	H	H	H	0.760	Relevant
B23	VH	H	H	H	M	H	VH	0.672	Relevant
B24	H	H	VH	H	H	M	VH	0.672	Relevant
B25	VH	H	H	H	VH	H	H	0.771	Relevant
B26	H	VH	H	M	H	H	VH	0.672	Relevant
B27	H	H	VH	H	H	VH	H	0.771	Relevant
B28	H	VH	H	H	H	H	VH	0.771	Relevant
B29	H	H	VH	M	H	VH	H	0.672	Relevant
B30	H	VH	H	H	M	H	VH	0.672	Relevant
B31	H	H	H	M	VH	H	H	0.662	Relevant
B32	VH	H	H	H	VH	M	H	0.672	Relevant
B33	H	VH	H	H	H	H	VH	0.771	Relevant
B34	H	H	VH	H	M	H	VH	0.672	Relevant
B35	VH	H	H	H	VH	H	M	0.672	Relevant
B36	H	VH	H	H	H	M	VH	0.672	Relevant
B37	H	H	VH	H	VH	H	H	0.771	Relevant
B38	VH	H	H	H	M	VH	H	0.672	Relevant
B39	H	VH	H	H	VH	H	H	0.771	Relevant
B40	VH	H	H	H	VH	H	M	0.672	Relevant
B41	H	VH	H	H	VH	H	H	0.771	Relevant
B42	H	VH	H	H	H	H	VH	0.771	Relevant
B43	H	H	VH	H	M	H	VH	0.672	Relevant
B44	VH	H	H	H	VH	H	H	0.771	Relevant
B45	L	VL	M	L	VL	L	M	0.250	Not Relevant
B46	VL	L	L	M	L	VL	L	0.250	Not Relevant
B47	VH	H	H	H	VH	H	H	0.771	Relevant
B48	H	H	VH	H	M	H	VH	0.672	Relevant
B49	VH	H	H	H	VH	H	M	0.6728	Relevant

Table 9. Assessment of barrier dimensions.

	T	Tec	RP	EI	OM	OSC	MC	SA
Best	EI	VI	VI	AI	EI	VI	VI	AI
Worst	SA	FI	VI	AI	AI	VI	VI	EI

Table 10. Assessment of barriers within the technology dimension.

	B1	B3	B5
Best	B5	AI	WI
Worst	B1	EI	VI

Table 11. Assessment of barriers within the technical dimension.

		B6	B7	B8	B9	B10
Best	B7	VI	EI	WI	VI	AI
Worst	B10	WI	AI	VI	WI	EI

Table 12. Assessment of barriers within the regulations & policies dimension.

		B11	B12	B13	B14
Best	B11	EI	AI	AI	VI
Worst	B13	AI	WI	EI	VI

Table 13. Assessment of barriers within the economy & investment dimension.

		B16	B17	B18	B19	B20
Best	B16	EI	WI	AI	WI	FI
Worst	B18	AI	VI	EI	VI	VI

Table 14. Assessment of barriers within the organization & management dimension.

		B21	B22	B23	B24	B25	B26	B27	B28	B29
Best	B22	WI	EI	WI	FI	FI	FI	VI	VI	AI
Worst	B29	AI	AI	VI	FI	FI	FI	WI	WI	EI

Table 15. Assessment of barriers within the Operations and Supply Chain (OSC) dimension.

		B30	B31	B32	B33	B34	B35	B36	B37
Best	B32	VI	AI	EI	VI	VI	AI	AI	AI
Worst	B36	VI	FI	AI	VI	VI	FI	EI	WI

Table 16. Assessment of barriers within the Market and Competition (MC) dimension.

		B38	B39	B40	B41	B42	B43	B44
Best	B38	EI	WI	FI	FI	AI	VI	VI
Worst	B42	AI	VI	FI	FI	EI	WI	WI

Table 17. Assessment of Barriers within the Social and Awareness (SA) Dimension

		B47	B48	B49
Best	B47	EI	VI	AI
Worst	B49	AI	VI	EI

Table 18. Assessment of Strategies on Each Barrier.

Barriers / Strategies	S1	S2	S3	S4	S5	S6	S7
B1	M	L	L	L	M	VH	M
B3	L	M	H	L	M	H	VH
B5	M	M	L	L	M	H	VH
B6	L	H	M	M	H	M	H
B7	H	M	M	L	L	M	VH
B8	M	H	L	L	VH	M	M
B9	L	M	VH	M	M	L	M
B10	L	L	M	L	M	VH	M
B11	VH	H	M	H	M	M	M

Table 18 (continue). Assessment of Strategies on Each Barrier.

Barriers / Strategies	S1	S2	S3	S4	S5	S6	S7
B1	M	L	L	L	M	VH	M
B3	L	M	H	L	M	H	VH
B5	M	M	L	L	M	H	VH
B6	L	H	M	M	H	M	H
B7	H	M	M	L	L	M	VH
B8	M	H	L	L	VH	M	M
B9	L	M	VH	M	M	L	M
B10	L	L	M	L	M	VH	M
B11	VH	H	M	H	M	M	M
B12	H	M	M	VH	M	L	L
B13	VH	M	L	H	M	L	L
B14	H	M	M	VH	L	L	L
B16	VH	H	M	M	L	H	H
B17	H	H	L	M	M	L	L
B18	H	M	L	M	L	H	M
B19	VH	H	L	M	L	M	M
B20	H	M	L	M	L	M	M
B21	M	H	M	L	H	L	M
B22	M	H	L	M	H	L	M
B23	M	H	L	M	H	L	L
B24	L	H	L	M	H	L	M
B25	M	M	VH	VH	M	L	L
B26	H	H	L	M	M	L	L
B27	L	VH	L	M	H	L	M
B28	VH	M	L	M	M	L	L
B29	L	M	VH	M	M	L	L
B30	M	H	M	L	L	L	VH
B31	L	M	VH	M	M	L	H
B32	M	M	M	L	L	M	VH
B33	M	M	M	L	L	M	VH
B34	H	M	L	L	L	L	VH
B35	H	M	L	L	L	L	M
B36	M	H	L	L	L	M	M
B37	L	H	L	M	H	L	L
B38	M	H	L	L	VH	H	M
B39	L	L	L	M	VH	H	M
B40	L	VH	M	M	H	L	H
B41	M	H	M	L	L	L	VH
B42	L	L	L	M	M	VH	M
B43	M	L	M	VH	L	L	L
B44	M	L	M	VH	L	L	L
B47	L	M	L	M	VH	M	L
B48	L	M	L	M	H	L	L
B49	L	L	L	M	VH	H	M

4. RESULTS AND DISCUSSION

4.1. Results of Weighting Barriers with Fuzzy BW

The weighting analysis using the Fuzzy BWM indicates that economic and investment-related barriers dominate the challenges in adopting a circular rice supply chain. This finding highlights a critical insight: the successful transition toward circularity is not solely a

technological or managerial issue but is primarily constrained by financial and economic feasibility. As shown in **Table 19**, the barrier “high financial costs and risks in investment and operations” (B16) emerged as the most significant, with a global weight of 0.0872, ranking first among all 49 barriers. Closely following are the short-term perspective on economic benefits (B17) and the prioritization of capital expenditure over operational expenditure (B19), both of which underscore the strong influence of financial decision-making patterns. The low price of virgin raw materials (B20) also ranked high (5th), highlighting the structural disadvantage of circular practices compared to conventional production.

Beyond the economic dimension, regulatory and policy-related barriers were also highly influential. Lack of government support and incentives (B11) ranked second overall, with a global weight of 0.0659, reflecting the pivotal role of state intervention in providing fiscal and regulatory frameworks that can reduce investment risks and encourage circular adoption. Other regulatory gaps, such as the absence of global standards for CSCM performance (B14), ranked 12th, emphasizing the importance of harmonized benchmarks to assess and drive sustainability performance. Technical constraints were also notable. Inadequate collection centers and recycling facilities (B7) ranked 6th with a weight of 0.0418, while the lack of technical expertise and skilled human resources (B8) ranked 7th, highlighting operational challenges in implementing circular models in rice supply chains that rely heavily on smallholder farmers. Similarly, infrastructure incompatibility within the supply chain (B32) ranked 8th, reflecting logistical and systemic readiness issues.

Market- and consumer-related challenges also contributed to a set of barriers that cannot be overlooked. Limited training on circular technologies and waste management (B38) ranked 9th, while negative consumer perceptions of circular products (B39) ranked 13th. These findings indicate that gaps in awareness and consumer acceptance represent critical bottlenecks that could undermine the viability of circular rice products. Additionally, the barrier of insufficient public knowledge about circular technologies (B47) from the social and awareness dimension ranked 11th, emphasizing the importance of knowledge dissemination and behavioral change. In contrast, technology-related barriers, such as the complexity of recycling rice husk waste (B3) and the lack of product recycling for husk-to-biomass conversion (B5), were ranked 14th and 10th, respectively. This suggests that while technical issues exist, they are not as critical as financial and regulatory challenges. Lower-ranked barriers, including an organizational culture reliant on traditional practices (B37), lack of reliable information (B29), and unsupportive consumer behavior (B49), reflect structural and cultural factors that, although less dominant, still require targeted interventions.

The results of this study highlight that financial and cost-related factors are the primary obstacles to transforming the rice supply chain into a circular model, providing empirical confirmation that economic viability forms the backbone of circular adoption. This is evident from the highest-ranked barrier, B16 – high financial costs and risks in investment and operations – which emerged as the most influential factor hindering the adoption of circular practices. This finding aligns with prior studies [10,14-16,19], which similarly identified high investment costs and financing risks as structural bottlenecks in circular supply chain transitions. Previous research emphasized that implementing new technologies and establishing recycling infrastructure requires substantial upfront investment [39], while short-term returns are often minimal [40]. Our study extends this evidence by showing that in the rice sector, these costs are not limited to infrastructure but also encompass reverse logistics systems, biomass energy conversion facilities, digital traceability technologies, ongoing maintenance, and the need for skilled labor [41]. These requirements place immense pressure on smallholders and SMEs, who are financially constrained and highly vulnerable to market

fluctuations. Consequently, B16 emerges as the most critical barrier, as circularity initiatives cannot achieve sustainability without robust financial support.

The second most significant barrier, B11 – lack of government support and incentives – underscores the pivotal role of public policy in enabling the transition to circularity. Our findings indicate that insufficient fiscal and regulatory support exacerbates the financial burden on farmers and rice millers, discouraging long-term investments in circular technologies. Previous studies [14,15,17] have similarly emphasized that the absence of subsidies, tax breaks, or soft loans deters businesses from shifting away from linear models. Literature further shows that proactive policy instruments such as low-interest credit schemes, subsidies, or refund mechanisms are indispensable drivers of the circular economy. Conversely, weak regulatory and fiscal frameworks perpetuate reliance on conventional practices [42]. By highlighting the significance of B11, this study confirms that policy support is not merely complementary but a prerequisite for engaging all actors across the rice supply chain.

Other highly ranked barriers, including B17 (short-term perspective on economic benefits) and B19 (prioritization of capital expenditure over operational expenditure), both received identical global weights (0.0643), ranking third and fourth, respectively. These findings underscore the structural issue of economic short-termism among rice supply chain actors. Previous studies [43] similarly observed that actors often prioritize immediate gains over long-term sustainability. In circular rice practices, the extended payback period for investments reduces their attractiveness compared to linear operations. B17 reflects the tendency of farmers, rice millers, and distributors to focus on quick profits, which directly impedes the adoption of circular technologies such as biomass energy production or reverse logistics systems.

Meanwhile, B19 reveals that even when capital is available, it is primarily allocated to asset purchases and infrastructure rather than recurring costs such as maintenance of eco-friendly technologies, workforce training, and monitoring systems [44]. This bias undermines continuity, indicating that the success of circular supply chains depends not only on capital investments but also on the consistent allocation of operational budgets. Together, B17 and B19 highlight the need for a paradigm shift in financial planning that balances short-term returns with long-term operational sustainability.

The fifth-ranked barrier, B20 – low price of virgin raw materials further undermines the competitiveness of recycled products within the rice supply chain. When rice husk, paddy, or other primary raw materials are relatively inexpensive, recycled alternatives such as biomass energy or animal feed become less economically viable. This situation reduces the incentive for actors to invest in circular technologies, as the additional costs cannot be recovered in competitive markets. The finding aligns with previous research in agricultural and manufacturing sectors, which consistently reported that low primary resource prices diminish the attractiveness of recycled alternatives. Consequently, circularity often becomes a secondary rather than primary choice, despite its sustainability benefits. Our study reinforces this argument by demonstrating that in the rice sector, B20 functions as a critical structural barrier, solidifying the dominance of linear practices even when circular solutions are technologically feasible.

Table 19. Weighting Results with Fuzzy BWM.

Dimension	Dimension Weight	Barriers	Code	Barrier Indicator Weight	Global Barrier Weight	Rank
Technology (T)	0.0656	Limited eco-friendly technology and innovation for waste processing (rice husk, wastewater, etc.)	B1	0.1251	0.0082	38
		Complexity in recycling rice husk waste, washing water, and bran	B3	0.3939	0.0258	14
		Lack of product recycling related to limited circular reuse efforts, such as husk-to-biomass energy or animal feed	B5	0.4811	0.0316	10
Technical (Tec)	0.1150	Lack of operational models and technical methods for the Circular Supply Chain	B6	0.1161	0.0134	27
		Inadequate collection centers and recycling facilities, including the absence of husk banks or bran hubs	B7	0.3637	0.0418	6
		Lack of human resources and technical expertise in implementing Circular Supply Chains, including many farmers and business actors unfamiliar with circular practices	B8	0.3067	0.0353	7
		Lack of information systems to track recycled materials into products	B9	0.1161	0.0134	28
		Lack of circular design and innovative rice packaging to reduce food waste	B10	0.0974	0.0112	29
Regulations and Policies (RP)	0.1237	Lack of government support and incentives (regulatory and financial)	B11	0.5324	0.0659	2
		Absence of regulatory frameworks, standards, and technical guidelines	B12	0.1128	0.0140	25
		Weak enforcement of environmental protection rules and regulations	B13	0.1113	0.0138	26
		Lack of global standards to measure CSCM performance	B14	0.2435	0.0301	12
Economy and Investment (EI)	0.2896	High financial costs and risks in investment and operations	B16	0.3012	0.0872	1
		Short-term perspective on economic benefits	B17	0.2222	0.0643	3
		Higher prices of recycled products	B18	0.0693	0.0201	16
		Capital expenditure is prioritized over operational expenditure	B19	0.2222	0.0643	4
		The low price of virgin raw materials makes circular processes economically unattractive	B20	0.1852	0.0536	5

Table 19 (continue). Weighting Results with Fuzzy BWM.

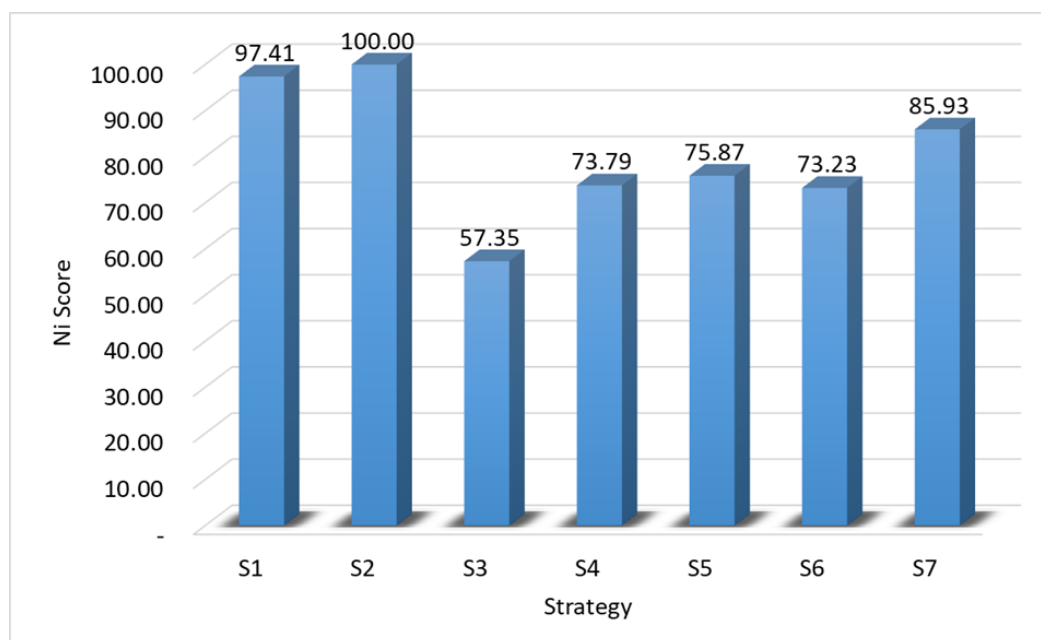
Dimension	Dimension Weight	Barriers	Code	Barrier Indicator Weight	Global Barrier Weight	Rank
Organization and Management (OM)	0.1150	Lack of stakeholder support and awareness	B21	0.1706	0.0196	17
		Resistance from legacy business models	B22	0.1976	0.0227	15
		Absence of a proper long-term vision for sustainability and scalability	B23	0.1706	0.0196	18
		Low industry participation	B24	0.0959	0.0110	30
		Absence of standardized systems for performance evaluation	B25	0.0959	0.0110	31
		Risk aversion	B26	0.0959	0.0110	32
		Lack of flexibility and coordination across departments	B27	0.0602	0.0069	41
		Inadequate environmental programs	B28	0.0602	0.0069	42
		Lack of reliable information	B29	0.0529	0.0061	44
Operations and Supply Chain (OSC)	0.1150	Complex supply chain networks	B30	0.1383	0.0159	21
		Lack of accurate estimates of waste quantity and type	B31	0.0781	0.0090	36
		Incompatible infrastructure and operations	B32	0.2988	0.0344	8
		Absence of efficient waste management systems	B33	0.1383	0.0159	22
		High transportation costs	B34	0.1383	0.0159	23
		Increasing uncertainty	B35	0.0785	0.0090	35
		Limited quality partners within the supply chain	B36	0.0632	0.0073	40
		Organizational culture is dependent on traditional practices	B37	0.0664	0.0076	39
Market and Competition (MC)	0.1237	Limited training and development on circular technology and waste management among stakeholders	B38	0.2670	0.0330	9
		Low acceptance and negative consumer perception of circular products	B39	0.2276	0.0282	13
		Lack of collaboration and information exchange among supply chain actors (e.g., fertilizers or feed from waste perceived as inferior)	B40	0.1334	0.0165	19
		Absence of integrated reverse logistics networks for packaging, husks, used sacks, etc.	B41	0.1334	0.0165	20
		Brand image	B42	0.0706	0.0087	37
		Lack of standardization for product modernization	B43	0.0840	0.0104	33
		Limited access to product recycling	B44	0.0840	0.0104	34

Table 19 (continue). Weighting Results with Fuzzy BWM.

Dimension	Dimension Weight	Barriers	Code	Barrier Indicator Weight	Global Barrier Weight	Rank
Social and Awareness (SA)	0.0522	Lack of public knowledge of circular technologies	B47	0.5995	0.0313	11
		Weak social and cultural pressure toward the Circular Economy	B48	0.2749	0.0143	24
		Unsupportive consumer behavior (unwilling to pay, unsustainable usage of products)	B49	0.1256	0.0066	43

4.2. Results and Discussion of Strategy Selection with Fuzzy COPRAS

The analysis using the Fuzzy COPRAS method, as presented in **Figure 2**, shows that S2 building a partnership platform among government, farmer cooperatives, private actors, and financial institutions to share investment costs in circular technologies achieved the highest score of 100. This result underscores that multi-stakeholder collaboration is the most effective strategy for overcoming financial barriers and investment risks, previously identified as the most critical obstacles to adopting a circular rice supply chain. The prioritization of S2 indicates that a single actor cannot mitigate financial risks alone; instead, collaborative investment schemes foster shared responsibility and trust across the supply chain. These findings align with previous research emphasizing collaboration as a key mechanism for resource pooling and reducing investment uncertainties in circular economy transitions [10,14,16,19]. However, this study advances the literature by providing quantified empirical evidence in the context of the rice supply chain, an area seldom explored using integrated fuzzy MCDM approaches.

**Figure 2.** The analysis using the Fuzzy COPRAS method.

The second-ranked strategy, S1 – provision of green subsidies or tax incentive schemes for farmers, rice milling SMEs, and agribusiness actors – scored 97.41, highlighting the critical role of fiscal and policy incentives in accelerating circular adoption. This finding corroborates prior

studies that identified government incentives as essential for reducing high upfront investment burdens and encouraging long-term adoption of sustainable practices [15,17]. By positioning S1 just behind S2, the study emphasizes the complementarity between collaborative platforms and governmental fiscal support. Practically, while S2 mitigates investment risk through shared responsibility, S1 directly reduces financial costs via subsidies and tax relief. Together, these strategies provide a dual mechanism to unlock capital-intensive circular investments.

The third-priority strategy, S7 – establishment of circular logistics hubs in rice production centers – scored 85.93, emphasizing the importance of operational and supply chain integration. This strategy directly addresses operational barriers such as infrastructure incompatibility and the lack of waste management systems, which were identified as significant obstacles in the barrier analysis. By creating hubs for reverse logistics, rice husk and by-products can be efficiently collected, processed, and converted into biomass energy, fertilizers, or industrial raw materials. These findings are consistent with prior research that recognized logistics hubs as enablers of resource efficiency and circularity in agricultural systems [19]. Notably, this study highlights the direct prioritization of logistics hubs in the rice sector, reinforcing their strategic role in operationalizing circular practices at scale.

The fourth-ranked strategy, S5 (tiered training programs and circular literacy campaigns), scored 75.87, demonstrating that human resource capacity building and consumer awareness are indispensable for sustaining circular transitions. While financial and operational strategies address structural barriers, S5 targets behavioral and cultural dimensions by enhancing skills, knowledge, and acceptance of circular practices. This finding complements earlier studies emphasizing the importance of training and awareness in embedding circular values within local communities. Importantly, the prioritization of S5 in this study underscores that without adequate literacy and training, even financially supported circular systems may fail to gain legitimacy and achieve long-term adoption.

Among the mid-range priorities, S4 (establishment of national standards and certification for circular products, score 73.79) and S6 (development of eco-friendly packaging designs and eco-label marketing, score 73.23) underscore the importance of institutional legitimacy and market acceptance. Standards and certifications set benchmarks for quality and environmental performance, enhancing consumer trust and facilitating wider adoption. Similarly, eco-labeling strengthens brand image and market differentiation for circular rice products. These findings align with previous literature highlighting the role of standards and eco-labels in promoting market legitimacy for sustainable products. Importantly, this study emphasizes their specific relevance to the rice supply chain, where consumer acceptance continues to be a key challenge.

Conversely, S3 (development of digital traceability systems) scored the lowest at 57.35. While digitalization offers long-term benefits such as transparency, accountability, and quality assurance, its current implementation is constrained by high technological costs and inadequate digital infrastructure in rural areas. Although previous studies have recognized the potential of IoT and blockchain for supply chain traceability, the findings here indicate that, in the rice sector, advanced digital technologies are secondary to more immediate strategies, such as financial support, multi-stakeholder collaboration, and logistics integration. This divergence highlights a key contribution of the study: the contextual prioritization of strategies that balance technological ambitions with financial and infrastructural readiness.

4.3. Implications Research

4.3.1. Theoretical Implications

The proposed framework developed in this study makes a notable theoretical contribution by integrating Fuzzy Delphi, Fuzzy BWM, and Fuzzy COPRAS into a comprehensive decision-making approach for evaluating barriers and prioritizing strategies in adopting a circular rice supply chain. While previous studies on circular supply chains have largely relied on single-method approaches (such as DEMATEL for mapping causal relationships, BWM for weighting barriers, or AHP/ANP for multi-criteria evaluations), they were often limited to either barrier identification or criterion weighting. In contrast, this research advances the literature by combining barrier identification, prioritization, and strategy selection within a single coherent framework. This integration ensures that the analysis goes beyond problem diagnosis and moves toward generating actionable, context-specific solutions, bridging a critical gap between descriptive and prescriptive models in circular supply chain studies.

Compared to earlier frameworks that focused mainly on manufacturing sectors such as plastics, automotive, or electronics, the framework presented here is specifically tailored to the agricultural and food supply chain, with a focus on rice, a staple of strategic importance in developing countries. By doing so, this study extends the theoretical applicability of fuzzy MCDM methods into a domain that has received relatively limited scholarly attention. Furthermore, the inclusion of diverse expert perspectives (from academia, government, farmer cooperatives, and industry) enhances the robustness of the framework, making it adaptable to multi-actor and resource-constrained environments where circular practices face systemic challenges.

The theoretical contribution of this integrated framework lies in its ability to facilitate an understanding of the multi-dimensional nature of barriers (financial, regulatory, technical, operational, organizational, market, and social) while simultaneously linking these barriers to specific prioritized strategies. This stands in contrast to previous studies, which often examined barriers in isolation and did not connect them to a coherent set of feasible interventions. By incorporating Fuzzy COPRAS in the final stage, the framework provides a structured approach for ranking strategies according to their effectiveness in addressing weighted barriers, thereby addressing the widely noted implementation-theory gap in circular economy research.

4.3.2. Managerial Implications

The results of this study suggest several important managerial implications for decision-makers and stakeholders in the rice supply chain. The prominence of financial and investment-related barriers (B16, B17, B19, and B20) underscores the urgent need for managers to adopt a long-term, pragmatic mindset rather than focusing solely on short-term gains. Implementing circular supply chains requires increased capital investment alongside ongoing operational expenditures for training, maintenance, and system monitoring. Consequently, managers are encouraged to revise financial policies to balance capital and operational budgets, ensuring continuity and robustness in circularity initiatives.

The findings also highlight that systemic barriers are most effectively addressed through multi-stakeholder collaboration (S2) and government fiscal incentives (S1). For practitioners, this entails prioritizing cross-chain linkages and integrating farmers, rice millers, cooperatives, private investors, and financial institutions within a collaborative management framework. Managers can act on these insights by actively participating in partnership platforms and consortia that facilitate risk-sharing and joint investment in innovation. Additionally,

managers should align their business models with available fiscal incentives, such as subsidies and tax breaks, to lower costs and promote the broader adoption of circular technologies.

The relatively high importance of operations- and logistics-oriented strategies (S7) highlights that managers must also focus on supply chain integration and efficiency. Establishing truck terminals and reverse logistics systems is both a technical and managerial challenge, requiring careful planning of material flows and the transformation of by-products, such as rice husks, into valuable resources. To achieve this, supply chain managers need to develop physical and digital infrastructures that enable traceability, collection, and redistribution of these resources efficiently.

Additionally, the findings underscore the significance of capacity building and awareness dissemination (S5) as essential managerial responsibilities. Managers should implement structured training programs for workers, farmers, and SMEs to ensure they understand and can apply circular practices. At the same time, managers can collaborate with marketing and communication teams to launch awareness campaigns that encourage consumer acceptance of circular rice products.

Finally, this study adds new information, especially relating to fuzzy applications, as reported elsewhere [45-48].

5. CONCLUSION

This study aimed to identify the most critical barriers and formulate prioritized strategies for implementing a circular rice supply chain in Indonesia using an integrated fuzzy multi-criteria decision-making framework. The findings indicate that financial and investment-related barriers, particularly the high costs and risks of investment and operations (B16), represent the most significant challenge. Other prominent barriers include the lack of government support and fiscal incentives (B11), short-term economic perspectives (B17), prioritization of capital expenditure over operational expenditure (B19), and the low price of virgin raw materials (B20). Collectively, these barriers suggest that the adoption of circular supply chains is constrained more by systemic financial, regulatory, and economic structures than by technological feasibility. The strategy prioritization using Fuzzy COPRAS demonstrates that multi-stakeholder collaboration (S2) and fiscal incentives (S1) are the most effective interventions to overcome these obstacles. Complementary measures, such as operational integration through circular logistics hubs (S7) and human capital development via training and literacy campaigns (S5), further enhance implementation. Secondary strategies, including standardization (S4), eco-labeling and packaging innovation (S6), and digital traceability systems (S3), strengthen legitimacy and consumer acceptance, though their success depends on adequate financing and infrastructure readiness. Overall, these results highlight that the sustainable transformation of rice supply chains requires an integrated approach that aligns financial mechanisms, regulatory frameworks, and managerial practices with circular economy principles.

The key contribution of this study lies in its holistic and integrated framework, which combines Fuzzy Delphi for barrier validation, Fuzzy BWM for weighting, and Fuzzy COPRAS for strategy prioritization. Unlike earlier studies that focused solely on barrier identification or weighting within isolated industrial sectors, this research provides a systematic pathway from problem identification to solution prioritization, specifically for a staple agricultural commodity. This advancement enriches the theoretical understanding of circular supply chain management by offering a replicable model that integrates multidimensional barriers with actionable strategies. The practical implications are equally significant. Policymakers gain a robust evidence base for designing fiscal and regulatory interventions, managers obtain a

roadmap for financial and operational planning, and stakeholders can identify collaborative pathways to reduce risks and costs. By bridging academic rigor with practical applicability, the study enhances the strategic relevance of circular supply chain research in agri-food systems. Future research could extend this framework by incorporating dynamic and temporal dimensions, such as shifts in consumer preferences, market volatility, or rates of technological adoption. Methodologically, integrating fuzzy approaches with system dynamics or agent-based modeling could simulate long-term outcomes of circular strategies under varying policy and market conditions. Moreover, applying the framework to other food supply chains beyond rice would broaden its generalizability and provide additional insights into sustainable agri-food systems.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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