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A hybrid fuzzy SWARA-COPRAS framework to evaluate sustainable co-firing in coal power plants: A case study from Indonesia

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ABSTRACT

The transition to sustainable energy encourages various countries, including Indonesia, to adopt Co-Firing technology to reduce carbon emissions without requiring significant investments in power plant infrastructure. The selection of appropriate biomass materials, based on sustainability dimensions, significantly influences the success of Co-Firing implementation. This study proposes a hybrid framework that integrates the Fuzzy SWARA and Fuzzy COPRAS methods to holistically evaluate Co-Firing alternatives, considering technical, economic, environmental, social, and supply chain aspects. A case study was conducted at a power plant in Indonesia, involving four experts from the industry and academia to assess 23 sustainability sub-criteria and five biomass alternatives. The results indicate that the sub-criteria of water footprint, supplier reliability, local job creation, and co-firing retrofit cost are dominant factors in biomass selection. This research selected Alternative 2 (wood chips) as the most effective biomass material for implementation at power plants in Indonesia. Additionally, sensitivity analysis confirmed that biomass is the most stable alternative to changes in criteria weights, which offers high flexibility in the supply chain and circular economic potential. These findings contribute theoretically to developing multi-criteria decision-making methods based on fuzzy logic and practically support policymakers and industry in planning sustainable and adaptive Co-Firing strategies in the face of uncertainty.

1. INTRODUCTION

Co-firing is a combustion method that combines biomass with fossil fuels such as coal in power generation. This strategy is considered effective in supporting the energy transition as it reduces carbon dioxide (CO_2) emissions without requiring significant investments in infrastructure modifications [1], [2]. Using biomass in proportions of 10-20% can reduce CO_2 emissions by 15-30%, depending on the type and quality of the biomass used [3], [4]. In addition to providing environmental benefits, Co-Firing also improves national energy security by utilising local resources, such as agricultural waste, thereby reducing dependence on coal imports and mitigating fossil fuel price fluctuations [5], [6], [7]. However, its implementation is not free from challenges such as variability in biomass quality that can affect combustion efficiency and the need for complex operational adjustments [8], [9]. In addition, high logistics costs, especially in regions with limited infrastructure, are a significant concern [10], [11], [12]. Therefore, a sustainability approach that includes environmental, economic, and social dimensions is essential to ensure the long-term viability of co-firing applications [13], [14], [15].

From a sustainability perspective, the three pillars of environment, economy, and society should be considered equally in evaluating Co-firing [16], [17]. Environmentally, biomass should fulfil the principle of carbon neutrality, i.e., CO_2 emissions from its combustion should be balanced with the amount of carbon sequestered during its growth period [18], [19], [20]. Agricultural wastes such as rice husks and corn stover generally fulfil this principle. However, clearing forests for energy crops such as palm oil can erase the climate benefits gained [21], [22]. From an economic perspective, sustainability is determined by the cost of biomass production, energy conversion efficiency, and the availability of incentive policies such as feed-in tariffs or Renewable Energy Certificates [23], [24], [25]. Social aspects include the creation of new jobs, especially in the agriculture and forestry sectors, but also potential conflicts related to land access [26], [27], [28]. In addition to these three aspects, the technical selection of biomass species is also crucial, taking into account calorific value, moisture content, ash content, and potential impacts such as slagging and fouling [29], [30], [31]. Local availability also determines logistical efficiency and continuity of supply [32], where materials such as rice husks and oil palm empty fruit bunches (EFB) offer great potential in Indonesia [33], [34]. Therefore, a multidisciplinary approach is needed to optimally evaluate and select co-firing materials based on comprehensive sustainability criteria [35], [36].

Previous studies have examined the technical, economic, and policy dimensions of Co-Firing implementation, focusing on improving efficiency through variations in biomass composition, optimising combustion conditions, and utilising financial incentives and emissions regulations [37]. Several studies used Multi-Criteria Decision Making (MCDM) approaches, such as AHP, TOPSIS, and VIKOR, to evaluate and select the optimal generation technology and biomass type [38], [39], [40]. Additionally, fuzzy-based MCDM approaches have been employed to evaluate the feasibility of biomass in the context of sustainability. However, they are generally limited to one-dimensional evaluation and do not consider the complexity of the entire supply chain [41], [42], [43]. Some studies have also integrated lifecycle assessment (LCA) analysis with cost optimization to evaluate the environmental and economic impacts of co-firing [44], [45]. However, most of these studies have limitations in dealing with data uncertainty and the diverse preferences of stakeholders. Reliance on deterministic assumptions in criteria assessment often reduces the validity of the analysis results, especially when facing volatile market conditions or dynamic policies [46], [47]. Social and environmental aspects have been mentioned in several studies [48], but not many have systematically integrated them into a decision-making framework that reflects the perspectives of government, industry, and society simultaneously. Therefore, there remains an urgent need to develop a more holistic and adaptive evaluation approach that can accommodate uncertainty and take into account the preferences of the various parties involved in Co-Firing implementation.

Although studies on co-firing have increased, several key gaps in the literature remain unaddressed. One is the absence of an evaluation framework that comprehensively incorporates environmental, economic, social, and technical aspects in the context of Co-Firing [46], [48]. In addition, many conventional Multi-Criteria Decision Making (MCDM) methods still ignore data uncertainty as variations in preferences of different stakeholders [49], [50]. The lack of studies exacerbates this issue, particularly in developing countries, where biomass is abundant but supporting infrastructure, such as supply chains and processing technologies, is limited [51]. Most studies also focus on technical or economic aspects separately, without considering the interrelationships between sustainability dimensions [52], [53]. In addition, methods such as AHP are still widely used deterministically, making them prone to subjective bias and unable to capture linguistic uncertainties that arise in the expert judgment process.

Although studies on Co-Firing technology have made significant progress, important gaps still remain in the literature. Most previous studies have only emphasized one or two dimensions of sustainability, particularly technical and economic aspects, without systematically integrating social and supply chain dimensions into a comprehensive evaluation framework [46], [48], [49], [50]. In addition, conventional multi-criteria decision-making (MCDM) methods that are widely used, such as AHP and TOPSIS, still rely on deterministic approaches that tend to ignore data uncertainty and variations in stakeholder preferences. This reduces the validity of the analysis results, especially in developing countries such as Indonesia, where market conditions and policies are highly dynamic. Furthermore, available literature work using a holistic approach is insufficient to aid strategic decision-making in choosing adaptive and sustainable co-firing materials. Moreover, the inadequacy of geography conditions and local biomass composition in the evaluation makes it more imperative to establish a comprehensive, compendious, and field-based assessment model. Therefore, A new perspective is required to address multi-stakeholder complexity and simultaneously integrate technical, economic, environmental, social, and supply chain dimensions holistically in a decision-making frame that is adaptive to uncertainty.

In response to this gap, this research proposes an integrative approach by combining the Fuzzy SWARA (Step-wise Weight Assessment Ratio Analysis) and Fuzzy COPRAS (Complex Proportional Assessment) methods to evaluate Co-Firing supply chain solutions more adaptively [54], [55], [56]. Researchers utilize

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Fuzzy SWARA to determine criteria weights by considering uncertainty in expert judgment [57]. At the same time, Fuzzy COPRAS ranks alternatives based on relative closeness to the ideal solution [58]. The integration of these two methods is strengthened by sensitivity analysis to test the robustness of the results to variations in criteria weights and policy scenarios [59]. The case study was conducted on power plants in Indonesia, considering the availability of local biomass such as rice husk and oil palm empty fruit bunches, which are considered potential co-firing feedstock [60].

This research aims to identify key sustainability criteria for Co-Firing and develop a Fuzzy SWARA-COPRAS-based evaluation framework that can accommodate the uncertainty and complexity of multi-stakeholder preferences. This approach will provide a more objective and adaptive ranking of co-firing supply chain solutions. This research's main contributions include refining the MCDM methodology by integrating technical, economic, social, and environmental aspects, as well as supply chain dimensions, in a single holistic analysis. In addition, the practical application in Indonesia's power generation context provides strategic value, which can serve as a reference for other developing countries with similar characteristics. The findings will inform policymakers, industry stakeholders, and investors in developing sustainable and inclusive energy transition strategies.

2. RELATED WORK

Co-Firing technology is an energy transition approach that utilizes the blending of coal and renewable fuels such as biomass or solid waste for power generation [61], [62]. The main advantage of Co-Firing is that it enables the use of existing combustion systems without requiring significant investments in new infrastructure. This research makes Co-Firing a strategic option in developing countries that still depend on coal as the primary energy source [63], [64]. Studies have shown that co-firing can reduce carbon dioxide emissions by up to 40%, depending on the proportion of biomass used [65]. In addition, implementing co-firing supports the energy sector's decarbonization agenda without compromising the reliability of the electricity supply. Co-firing also opens up opportunities to utilize industrial or agricultural organic waste as fuel, thereby supporting circular economy principles and waste reduction [66]. Nonetheless, the quality and consistency of the alternative fuel supply greatly influence the successful implementation of co-firing.

Differences in thermal characteristics, moisture content, and particle size between biomass and coal often pose technical challenges in co-firing systems [67]. Therefore, it is necessary to thoroughly evaluate the technical parameters and supply availability before establishing a long-term Co-firing strategy. The concept of sustainable energy focuses not only on reducing carbon emissions but also encompasses economic, social, and technical dimensions in an integrated manner [68]. Energy is declared sustainable if it can meet the current generation's needs without compromising future generations' capacity, in terms of ecology, cost, and social aspects. In this context, co-firing is assessed from its efficiency and the elements of social feasibility, public acceptance, and supply sustainability [69], [70]. The importance of a multi-dimensional approach in assessing sustainability lies in the fact that energy decisions, without considering social and economic factors, perspectives, ranging from energy efficiency to the are often ineffective in the long term. Therefore, the evaluation process of energy solutions must integrate various welfare of surrounding communities. In co-firing, sustainability considerations are often critical in selecting alternative fuel types. For example, although agricultural waste is abundant and cheap, unstable supply chains and potential land conflicts can reduce its sustainability aspects. Therefore, the selection of an appropriate Co-Firing solution requires an evaluation approach that is not only technical but also considers environmental and social factors in a balanced manner.

Table 1 presents the mapping of previous research contributions utilising MCDM methods to evaluate energy solutions, encompassing the five pillars of sustainability: technical, economic, social, environmental, and supply chain. Most previous studies only covered three to four dimensions of sustainability, mainly technical, economic, and environmental aspects [38], [41], [44]. The study by San Juan *et al.* [47] did include the supply chain dimension; however, its approach remained deterministic, failing to consider data uncertainty or dynamic stakeholder preferences. Other studies, such as Lipka & Szwed [48] and Elleuch *et al.* [50], attempted to combine the social and environmental dimensions, but did not explicitly examine the aspects of supplier contract flexibility or seasonal variability risk, which are crucial in the context of the biomass supply chain.

Furthermore, the methods used in previous studies generally only involve one or two stages of MCDM, such as AHP or TOPSIS, without integration with fuzzy approaches to handle linguistic uncertainty. Fuzzy approaches have begun to be applied, such as by Elleuch *et al.* [50] and Utama *et al.* [71], but have not been focused explicitly on biomass selection in the complex framework of co-firing. Even studies by Gheibdoust & Homayounfar [72] and Sivageerthi *et al.* [73], which use Fuzzy SWARA and SWARA, have not expanded their application to a combination of methods for holistic ranking of alternatives.

Thus, there is an important gap that has not been adequately addressed by previous literature: the need for a comprehensive evaluation framework that

Table 1. Literature review for MCDM

Author(s)	**Application Object**	**Method**	**Pillar of Sustainability**				
			Tech	**Eco**	**Soc**	**Envi**	**Supply Chain**
Krishankumar *et al.* [38]	Renewable Energy Source (RES)	q-Rung Orthopair Fuzzy Decision-Making Framework	v	v	v	v	
Kiser & Otero [42]	Nuclear Power Plant (NPP)	AHP	v	v	v		
Shatnawi *et al.* [44]	Renewable Energy Source (RES)	AHP	v	v	v	v	
Hernández-Torres *et al.* [41]	Technology selection for a power plant for the Off-industry	AHP & TOPSIS	v	v	v	v	
Mojaver *et al.* [74]	Combined Heat and Power (CHP) System with Solid Oxide Fuel Cell (SOFC)	Taguchi, AHP, TOPSIS	v			v	
San Juan *et al.* [47]	Biomass-Coal Co-Firing Supply Chain Optimization	Goal Programming	v	v		v	v
Li *et al.* [45]	Renewable Energy Priority Assesment Framework	ANP, WSM, TOPSIS, PROMETHEE, ELECTRE, VIKOR	v	v		v	
Lipka & Szwed [48]	Clean Coal Technology Selection for Power Sector Transition	SMART	v	v	v	v	
Elleuch *et al.* [50]	Energy Source Evaluation for Tunisia	Fuzzy Multi-Criteria Group Decision Making (FMCGDM)	v	v	v	v	
Utama *et al.* [71]	Open-Source ERP Selection for SMEs	Fuzzy AHP, Fuzzy TOPSIS	v	v			
Utama [75]	Green Supplier Selection	AHP, TOPSIS		v		v	v
Utama *et al.* [76]	Supplier selection	DEMATEL, ANP		v			v
Gheibdoust & Homayounfa [72]	Knowledge Management (Tourism)	Fuzzy SWARA			v		
Sivageerthi *et al.* [73]	Risk in Coal Supply Chain	SWARA					v
Hasheminezhad *et al.* [77]	Train Collision Risk	Fuzzy COPRAS, Fuzzy DEMATEL	v				
Hadadi & Shirmohammadi [78]	Road Critical Segments Identification	Wavelet Theory, MCDM	v				
Hadadi & Shirmohammadi [79]	Asphalt Performance Evaluation	Fuzzy logic	v				
This research	Coal Power Plant for Evaluating Sustainable Co-Firing Solutions	Fuzzy SWARA, Fuzzy COPRAS	v	v	v	v	v

integrates all pillars of sustainability while handling data uncertainty and addressing multi-stakeholder preference differences. This study closes that gap by proposing a combination of Fuzzy SWARA and Fuzzy COPRAS, which not only determines criteria weights flexibly but also ranks alternatives based on their proximity to the ideal solution. In addition, the supply chain dimension is explicitly included, unlike most previous studies, by considering supplier reliability, seasonal variability, and potential degradation during storage. This approach offers an evaluative solution that is more adaptable to market and policy dynamics and is applicable in developing countries, such as Indonesia.

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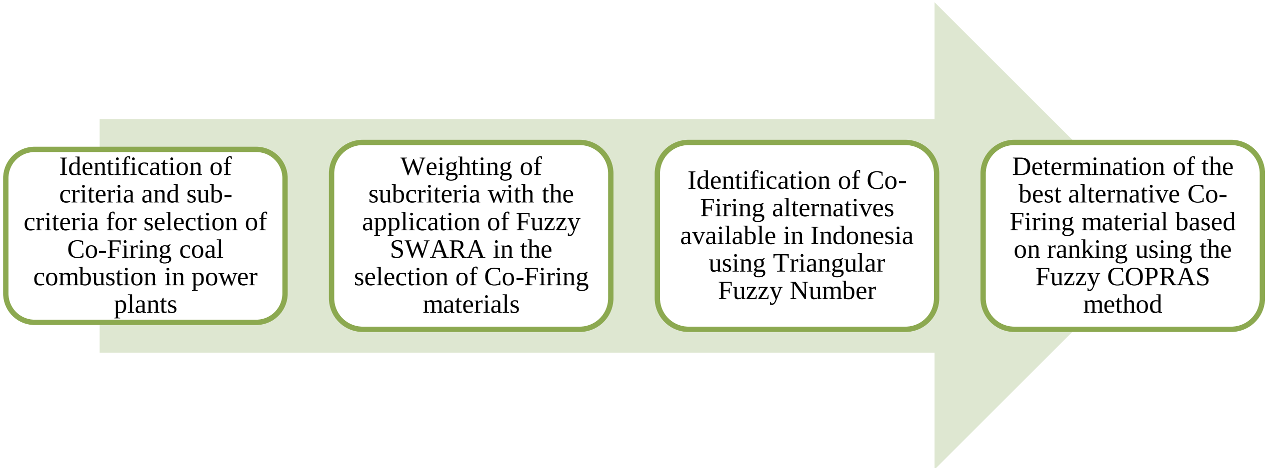

Fig.1. Co-firing selection framework

3. RESEARCH METHODS

This research methodology consists of four main stages in integrating Fuzzy SWARA and COPRAS. This paper proposes a framework for determining the best biomass material for coal combustion in power plants (Fig. 1). The first stage involves identifying and selecting criteria that support the co-firing process based on literature and expert opinions, including various sub-criteria. The second stage consists of weighting the subcriteria using the Fuzzy SWARA method. Fuzzy SWARA can be used to address the differences in significance among experts' assessments in the weighting process. This stage ensures that the Manager, Supervisors, and an Academic can systematically measure expert assessment differences. The third stage involves identifying alternative biomass materials with potential for use in the combustion process. At this stage, alternatives are selected based on the existing criteria and subcriteria. The final stage involves ranking the Co-Firing material alternatives using the Fuzzy COPRAS. This method identifies the best alternative by determining the ratio to the ideal solution and the ratio to the worst perfect solution.

The experts will assign a value to each sub-criterion using the scale in Table 2. Researchers then convert these values into fuzzy numbers, aggregate them, and defuzzify them before carrying out the step-wise SWARA process.

Table 2. Fuzzy scale for SWARA

Linguistic Scale	Triangular Fuzzy Number
Very Unimportant (VU)	(0.222, 0.25, 0.286)
Unimportant (U)	(0.286,0.333,0.4)
Medium (M)	(0.4,0.5,0.667)
Important (I)	(0.667,1,1.5)
Very Important (VI)	(1,1,1)

Step 1: Score each criterion based on expert opinion, prioritizing the most important ones as outlined in Table 2. Fuzzy Scale for SWARA

$$x_{ij}^{l} = \frac{\sum_{k=1}^{K} x_{ijk}^{l}}{K}, x_{ij}^{m} = \frac{\sum_{k=1}^{K} x_{ijk}^{m}}{K}, x_{ij}^{u} = \frac{\sum_{k=1}^{K} x_{ijk}^{u}}{K} \quad (1)$$

Step 2: Calculate the aggregate assessment collected from 4 experts, as shown in Equation (1).

$$x_{ij} = \frac{\left(x_{ij}^{l} - x_{ij}^{1}\right) + \left(x_{ij}^{m} - x_{ij}^{1}\right) + \left(x_{ij}^{u} - x_{ij}^{1}\right)}{3} \quad (2)$$

Then, defuzzification is performed, as in Equation (2), and the criteria are sorted from most important to least important.

$$\tilde{k}_j = \begin{cases} \tilde{1}; j = 1, \\ \tilde{s}_j + \tilde{1}; j > 1, \end{cases} \quad (3)$$

Step 3: The highest criterion is worth 1, and the following criterion is (j−1). Step 4: Determine the Coefficient value as in Equation (3).

$$\tilde{q}_j = \begin{cases} \tilde{1}; j = 1, \\ \frac{\tilde{q}_j - \tilde{1}}{k_j} + \tilde{1}; j > 1, \end{cases} \quad (4)$$

Step 5: determine the value of qj with Equation (4).

$$\tilde{w}_j = \frac{\tilde{q}_j}{\sum_{k=1}^{n} \tilde{q}_k} \quad (5)$$

Step 6: Calculate the wj value for each sub-criterion using the formula in Equation (5).

Table 3. Fuzzy number for COPRAS

Linguistic Scale	Triangular Fuzzy Number
Very Low (VL)	(0.222, 0.25, 0.286)
Low (L)	(0.286, 0.333, 0.4)
Medium (M)	(0.4, 0.5, 0.667)
High (H)	(0.667, 1, 1.5)
Very High (VH	(1.5, 2, 2.5)

Fuzzy COPRAS is used to evaluate and select the best alternative. Experts will provide an assessment of all alternatives based on Table 3. Fuzzy Number for COPRAS.

$$\tilde{X}\begin{bmatrix} (x_{11}^{l}, x_{11}^{m}, x_{11}^{u}) & (x_{12}^{l}, x_{12}^{m}, x_{12}^{u}) & (x_{1n}^{l}, x_{1n}^{m}, x_{1n}^{u}) \\ (x_{21}^{l}, x_{21}^{m}, x_{21}^{u}) & (x_{22}^{l}, x_{22}^{m}, x_{22}^{u}) & (x_{2n}^{l}, x_{2n}^{m}, x_{2n}^{u}) \\ \cdots & \cdots & \cdots \\ (x_{m1}^{l}, x_{m1}^{m}, x_{m1}^{u}) & (x_{m2}^{l}, x_{m2}^{m}, x_{m3}^{u}) & (x_{mn}^{l}, x_{mn}^{m}, x_{mn}^{u}) \end{bmatrix} \quad (6)$$

$$s_{ij}^{l} = \frac{x_{ij}^{l}}{\sqrt{\sum_{m}^{i=1}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \quad (7)$$

$$s_{ij}^{m} = \frac{x_{ij}^{m}}{\sqrt{\sum_{m}^{i=1}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \quad (8)$$

$$s_{ij}^{u} = \frac{x_{ij}^{u}}{\sqrt{\sum_{m}^{i=1}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \quad (9)$$

Then, arranged in a matrix like Equation (6), the assessment will normalized like Equations (7), (8), and (9).

$$x_{ij} = \frac{\left(x_{ij}^{l} - x_{ij}^{1}\right) + \left(x_{ij}^{m} - x_{ij}^{1}\right) + \left(x_{ij}^{u} - x_{ij}^{1}\right)}{3} \quad (10)$$

The normalization results will continue into the Defuzzification stage, as in Equation (10).

$$\tilde{P}_j = \sum_{j=1}^{m} \tilde{x}_{ij} \quad (11)$$

$$\tilde{R}_j = \sum_{j=k+1}^{m} \tilde{x}_{ij} \quad (12)$$

Calculate the weighted normalization based on the Fuzzy SWARA results. Next, add up the criteria that go into the Max decision, as in Equation (11), and do the same for the criteria with the Min decision in Equation (12).

$$R_{min} = min_j R_{j;}\ j = 1,2,\ldots\ldots,n \quad (13)$$

In the results of Equation (12), continue to look for the minimum value among the five criteria as in Equation (13).

$$Q_j = \tilde{P}_j + \frac{R_{min}\sum_{j=1}^{n} R_j}{R_j \sum_{j=1}^{n} \frac{R_{min}}{R_j}};\ j = 1,2,\ldots.,n \quad (14)$$

$$Q_j = \tilde{P}_j + \frac{\sum_{j=1}^{n} R_j}{R_j \sum_{j=1}^{n} \frac{1}{R_j}};\ j = 1,2,\ldots.,n \quad (15)$$

In Equation (14), calculate the relative weight of each alternative. It can also be written as in Equation (15).

Table 4. List of criteria and sub-criteria

Criteria	Sub Criteria	Code	Decision	Definition
Technical	Biomass availability	T1	Max	Amount of sustainably available biomass (tons/year).
	Pre-processing requirement	T2	Min	Pre-treatment of biomass before it is used for combustion.
	Maximum Co-Firing ratio (%)	T3	Max	The maximum percentage of biomass that can be mixed without boiler modification.
	Corrosion risk	T4	Min	Potential boiler damage due to alkali content in biomass
Economy	Biomass cost	EC1	Min	Biomass price per ton
	Logistic cost	EC2	Min	Biomass transportation and storage costs
	Co-Firing retrofit cost	EC3	Min	Coal Power Plant modification cost for Co-Firing
	Government subsidies	EC4	Max	Government financial incentives
	Carbon tax	EC5	Min	Carbon emission tax payable
Environmental	CO2 reduction vs coal	ENVR1	Max	Percentage reduction in CO2 emissions compared to coal.
	Land use change risk	ENVR2	Min	Land change impact
	Water footprint	ENVR3	Min	Water consumption per ton of biomass
	Noise Pollution Impact	ENVR4	Min	Noise level from the co-firing operation
	Circular Economy Potential	ENVR5	Max	Waste utilization potential
Social	Local job creation	S1	Max	The number of new jobs created by the public
	Public acceptance	S2	Max	Percentage of community support
	Reduced respiratory diseases	S3	Max	Decrease in respiratory disease cases per year.
Supply Chain	Supplier reliability	SC1	Max	Supplier's ability to fulfill the cooperation contract
	Seasonal variability	SC2	Min	Supply fluctuations
	Storage degradation	SC3	Min	Decrease in biomass mass during the storage process
	Contract flexibility	SC4	Max	Flexibility of contracts with suppliers

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$$K = max_j Q_j; j = 1,2, \ldots, n \quad (16)$$

$$N_j = \frac{Q_j}{Q_{max}} \times 100 \quad (17)$$

Then look for the maximum value based on the result in Equation (16), and calculate the utility of each alternative as in Equation (17).

3.1. Data and case studies

This study focuses on prioritizing the sustainability of Co-Firing in power plants in Indonesia. Indonesia is an agricultural country that generates significant waste from farm products. Experts have identified alternative biomass materials relevant to implementing FDG in power plants. The alternatives are Sawdust (Alternative 1), Wood Chips (Alternative 2), Palm Kernel Shell (Alternative 3), Rice Husk (Alternative 4), and Corn Cob (Alternative 5).

In this study, four experts comprehensively assessed the sustainability criteria for co-firing materials. The four experts consisted of a manager, two Supervisors, and an academic expert in the field of sustainability. Managers and supervisors can represent the needs required to select biomass for power plants. An academic perspective that focuses on sustainability also strengthens the assessment. The selection of four experts aims to obtain diverse and in-depth perspectives, thereby enabling the identification of comprehensive criteria. The research applied MCDM, prioritizing the quality and experience of the experts over the number of experts. Study Xiang *et al.* [56] successfully applied Fuzzy SWARA-COPRAS with three experts. Table 4 presents the identification of sustainability criteria. Table 5 shows the assessments of four experts regarding the criteria. Table 6 presents the results of the biomass criteria assessment, considering the sustainability of each co-firing material. This study shows that the significance level of each criterion evaluates alternatives more objectively.

The sub-criteria assessments by the experts are presented in Table 5, which contains the data for Fuzzy SWARA. In the form of a linguistic scale in accordance with Table 2. Fuzzy Scale for SWARA. The assessment is influenced by the perspective of each expert, such as knowledge related to power plant operations, experience, and sustainability systems. The results of the expert assessments will be used in the processing of the Fuzzy SWARA method.

Table 6 presents the experts' assessments for each biomass alternative on a linguistic scale, which will be converted into numbers according to Table 3. Fuzzy Number for COPRAS. These assessments will then be processed using the Fuzzy COPRAS method to produce the best alternative solution.

Table 5. Expert rating for sub-criteria

Sub-Criteria	DM1	DM2	DM3	DM4
T1	(0.667, 1, 1.5)	(0.667, 1, 1.5)	(0.286, 0.333, 0.4)	(1, 1, 1)
T2	(0.4, 0.5, 0.667)	(0.667, 1, 1.5)	(1, 1, 1)	(0.4, 0.5, 0.667)
T3	(1, 1, 1)	(0.667, 1, 1.5)	(0.667, 1, 1.5)	(0.4, 0.5, 0.667)
T4	(0.286, 0.333, 0.4)	(1, 1, 1)	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)
EC1	(0.222, 0.25, 0.286)	(0.222, 0.25, 0.286)	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)
EC2	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)	(0.4, 0.5, 0.667)
EC3	(0.667, 1, 1.5)	(1, 1, 1)	(0.667, 1, 1.5)	(1, 1, 1)
EC4	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)	(1, 1, 1)	(0.4, 0.5, 0.667)
EC5	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)	(0.667, 1, 1.5)	(0.667, 1, 1.5)
ENVR1	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(0.667, 1, 1.5)
ENVR2	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)
ENVR3	(0.667, 1, 1.5)	(0.667, 1, 1.5)	(0.667, 1, 1.5)	(0.667, 1, 1.5)
ENVR4	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)
ENVR5	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)	(0.286, 0.333, 0.4)	(0.286, 0.333, 0.4)
S1	(0.667, 1, 1.5)	(1, 1, 1)	(0.667, 1, 1.5)	(0.667, 1, 1.5)
S2	(1, 1, 1)	(0.667, 1, 1.5)	(1, 1, 1)	(0.4, 0.5, 0.667)
S3	(1, 1, 1)	(1, 1, 1)	(0.4, 0.5, 0.667)	(1, 1, 1)
SC1	(0.667, 1, 1.5)	(0.667, 1, 1.5)	(0.667, 1, 1.5)	(0.667, 1, 1.5)
SC2	(1, 1, 1)	(0.222, 0.25, 0.286)	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)
SC3	(0.4, 0.5, 0.667)	(0.667, 1, 1.5)	(0.4, 0.5, 0.667)	(0.4, 0.5, 0.667)
SC4	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(0.4, 0.5, 0.667)

Table 6. Expert rating for alternatives

Sub-criteria	Alternative				
	1	**2**	**3**	**4**	**5**
T1	VH	M	H	VH	M
T2	VL	M	M	L	M
T3	H	H	H	H	H
T4	L	L	M	L	M
EC1	VL	VL	M	L	VL
EC2	VL	M	VH	VL	L
EC3	M	M	H	L	M
EC4	M	H	M	M	M
EC5	L	L	L	L	L
ENVR1	M	L	VL	L	L
ENVR2	VL	L	H	M	M
ENVR3	VL	VL	VH	L	M
ENVR4	L	L	L	L	L
ENVR5	H	H	M	H	H
S1	L	M	H	M	M
S2	VH	VH	H	H	H
S3	M	M	H	M	H
SC1	VH	VH	VL	H	M
SC2	L	L	H	VL	L
SC3	VH	H	L	M	L
SC4	H	H	M	H	L

4. RESULTS AND DISCUSSION

4.1. Optimal alternative

This study successfully identified and prioritised biomass for co-firing in power plants using the Fuzzy SWARA and Fuzzy COPRAS methods, providing substantial theoretical contributions [55]. Based on the results, the main criteria for selecting biomass were found to be water footprint (ENVR3), supplier reliability (SC1), local job creation (S1), and co-firing retrofit cost (EC3). The four sub-criteria above represent each of the criteria considered in selecting biomass materials, which are presented in Table 7.

Table 7. Weighting results of biomass co-firing selection sub-criteria

Sub Criteria	Code	Weight	Rank
Biomass availability	T1	0,052	9
Pre-processing requirement	T2	0,048	10
Maximum co-firing ratio (%)	T3	0,055	6
Corrosion risk	T4	0,040	15
Biomass cost	EC1	0,030	21
Logistic cost	EC2	0,033	19
Co-firing retrofit cost	EC3	0,061	4
Government subsidies	EC4	0,042	14
Carbon tax	EC5	0,045	12
CO2 reduction vs coal	ENVR1	0,060	5
Land use change risk	ENVR2	0,037	17
Water footprint	ENVR3	0,070	1
Noise Pollution Impact	ENVR4	0,031	20
Circular Economy Potential	ENVR5	0,034	18
Local job creation	S1	0,062	3
Public acceptance	S2	0,054	7
Reduced respiratory diseases	S3	0,053	8
Supplier reliability	SC1	0,063	2
Seasonal variability	SC2	0,039	16
Storage degradation	SC3	0,043	13
Contract flexibility	SC4	0,047	11

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Weight distribution (Table 7) reinforces previous findings that a multidimensional approach is necessary to assess the sustainability of Co-Firing programs [36]. The dominance of sub-criteria from environmental, social, and supply chain dimensions confirms that co-firing success relies not solely on technical or economic feasibility but also on the balance of ecological impact, social benefit, and operational resilience. These findings align with Mishra *et al.* [55] and Ansari *et al.* [57], emphasizing fuzzy-based methods to accommodate expert uncertainty and subjective judgments in sustainability decision-making.

Compared to previous studies summarized (Table 1), this research offers several advantages. For example, studies by Krishankumar *et al.* [38], Kiser & Oter [42], and Shatnawi *et al.* [44] included technical, economic, and social dimensions but omitted the supply chain aspect, which is critical for co-firing implementation in developing countries. While San Juan *et al.* [47] focused on optimising biomass supply chains using deterministic goal programming, this study adds value by integrating fuzzy logic to handle linguistic uncertainty and varying stakeholder preferences.

However, this study also has limitations. Unlike Li *et al.* [45] and Lipka & Szwed [48], who adopted a broader MCDM framework with multiple methodological integrations, our approach involves only Fuzzy SWARA and COPRAS, with input from just four experts. Geographic diversity across Indonesia, where biomass availability varies greatly, was not explicitly addressed, limiting generalizability. Furthermore, the research lacks direct stakeholder involvement, which reduces the participatory depth compared to more inclusive frameworks, such as those in Elleuch *et al.* [50]. Despite these limitations, the localized context and robust sensitivity analysis still position this study as a meaningful advancement in adaptive co-firing evaluation.

Table 8. Material ranking results for biomass

Alt	1	2	3	4	5
N	99%	100%	59%	67%	94%

The results show that the score for each biomass material alternative is obtained through the Fuzzy SWARA method presented in Table 8. The calculation found that alternative 2 ranked first with a utility value of 100%. Alternative 2 most effectively uses Co-Firing, as determined by the established criteria and sub-criteria. Results are followed by Alternative 1, which is ranked second with a utility value of 99%. Meanwhile, the last rank is alternative 4 with a utility value of 67%. These findings suggest that Alternative 2 is the most suitable biomass material for co-firing in power plants, whereas Alternative 3 is less ideal. Alternative 2 (woodchip) is a high-quality wood industry waste product, making it ideal for use as a co-firing material. Alternative 2 (woodchip) was selected as the optimal biomass due to its ease of supply, operational stability, and low environmental impact [63]. Its advantages are supported by a study by Monedero *et al*. [31], which highlights the consistency of wood biomass quality in combustion. This results in more controlled and stable operating combustion temperatures. The implementtation of Co-Firing will accelerate the energy transition in Indonesia by supporting environmental sustainability and cost efficiency. Alternative 2 (woodchip) is likely to be implemented in all steam power plants in Indonesia due to its ease of use.

Contrast with alternative 3 (palm kernel shells) resulted in low performance in selecting biomass co-firing materials. The weakness of Alternative 3 (palm kernel shell) is sub-optimal due to logistical challenges and deforestation risks [21], in accordance with Truong *et al.* [65] analysis of the limitations of palm-based biomass in developing countries. Additionally, the process of growing oil palm involves clearing new land, which is not in line with environmental sustainability. These drawbacks make Alternative 3 (palm kernel shell) less suitable for general steam power generation in Indonesia.

4.2. Model validation

This section presents the validation of the results obtained from the Fuzzy SWARA-COPRAS framework. This validation was conducted to compare the rankings with those obtained using other methods, specifically Fuzzy AHP and Fuzzy TOPSIS, utilising the same experts and data. The ranking results using Fuzzy AHP and Fuzzy TOPSIS can be seen in Table 9.

Table 9. Rank of alternative based on fuzzy topsis

Alt	Normalization	Rank
1	0,596	2
2	0,622	1
3	0,523	4
4	0,510	5
5	0,576	3

The results of Fuzzy AHP and Fuzzy TOPSIS show that the rankings of alternatives produced by both methods are highly consistent, with only minor differences in the rankings of 4 and 5, which differ from the Fuzzy SWARA and Fuzzy COPRAS methods. This significant similarity is strong evidence of the model's stability. It demonstrates that, despite the differences in the methods used in the calculations, the final results converge with those of other commonly used methods. Thus, this validation confirms that the Fuzzy SWARA-COPRAS framework is a valid and reliable framework for evaluating co-firing alternatives.

4.3. Sensitivity analysis

Sensitivity analysis was conducted to test the ranking of Co-Firing biomass materials against changes in sub-criteria weights and alternatives in 5 scenarios presented in Table 10. This analysis aims to understand how variations in criterion priorities, such as an increased focus on cost or ease of use, affect the ranking of biomass alternatives and ensure the flexibility of solutions to changing needs. Sensitivity analysis was conducted by changing the weight priorities of the sub-criteria to determine how these changes affected the final ranking of alternatives. This approach makes it possible to test the stability of the model under different scenarios. In the first experiment, sub-criterion ENVR5 was considered more important for environmental sustainability. In the second experiment, sub-criterion T1 was deemed essential for providing Co-Firing materials. In the third experiment, the sub-criteria with the highest weight were EC2, namely logistics costs. In the fourth experiment, the most crucial sub-criterion was T2, namely the pre-process that must be carried out for each biomass before the combustion process with coal. In the fifth experiment, T3 is considered the most critical sub-criterion for maximizing biomass use in combustion.

Fig. 2 is a graphical representation of the sensitivity analysis results, illustrating the changes in ranking between scenarios. Alternative 2 consistently remains at the highest rank. The results show that alternative 2 is flexible in changing the priority of criteria, making it a reliable biomass option. Alternative 3 shows the lowest ranking in the three scenarios, because palm kernel shell has weaknesses in the circular economy concept, high logistics costs, and complicated processing before being used as co-firing. The results of this sensitivity analysis can be considered by management when selecting biomass for co-firing, taking into account the flexibility of the criteria that can change. Sensitivity analysis can be used as an evaluation tool to ensure the chosen biomass remains relevant and practical in response to evolving needs.

This study conducted a sensitivity analysis to examine the strengths of selecting sustainable co-firing. Sensitivity analysis aims to validate the final ranking of alternatives when there is variation in the assessment of sub-criterion weights during alternative selection. A total of five experiments were conducted, and it was found that changes in sub-criterion weights affected the ranking of alternatives (Fig. 2).

This research has the advantage of considering all the potential alternative biomass materials in Indonesia. This advantage can facilitate the implementation of co-firing in power plants. However, this study also has the disadvantage that it does not considering the geographical factor in Indonesia. Each region in Indonesia has different biomass potential, so it is impossible to generalize the use of Co-Firing in power plants.

Table 10. Sensitivity analysis of alternative selection

Code	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
T1	0,076	3	0,113	1	0,030	15	0,039	12	0,041	10
T2	0,034	12	0,031	14	0,052	8	0,126	1	0,020	19
T3	0,049	10	0,094	2	0,036	11	0,068	4	0,114	1
T4	0,021	16	0,054	9	0,091	2	0,062	5	0,038	11
EC1	0,009	21	0,025	16	0,027	17	0,022	19	0,014	20
EC2	0,012	19	0,013	21	0,100	1	0,026	17	0,013	21
EC3	0,067	7	0,064	5	0,068	5	0,062	5	0,026	16
EC4	0,024	15	0,022	18	0,062	7	0,090	2	0,059	7
EC5	0,068	6	0,065	4	0,069	4	0,075	3	0,104	2
ENVR1	0,065	8	0,062	6	0,065	6	0,047	9	0,062	6
ENVR2	0,017	18	0,016	20	0,027	17	0,042	11	0,073	4
ENVR3	0,098	2	0,037	13	0,040	10	0,032	15	0,031	13
ENVR4	0,011	20	0,044	11	0,023	20	0,015	20	0,028	14
ENVR5	0,118	1	0,049	10	0,052	8	0,029	16	0,034	12
S1	0,070	5	0,078	3	0,033	13	0,051	8	0,048	9
S2	0,047	11	0,044	12	0,021	21	0,035	13	0,072	5
S3	0,062	9	0,059	7	0,076	3	0,047	9	0,023	18
SC1	0,073	4	0,059	7	0,027	17	0,056	7	0,051	8
SC2	0,020	17	0,018	19	0,033	13	0,015	20	0,028	14
SC3	0,025	14	0,023	17	0,030	15	0,035	13	0,094	3
SC4	0,033	13	0,030	15	0,036	11	0,026	17	0,026	16

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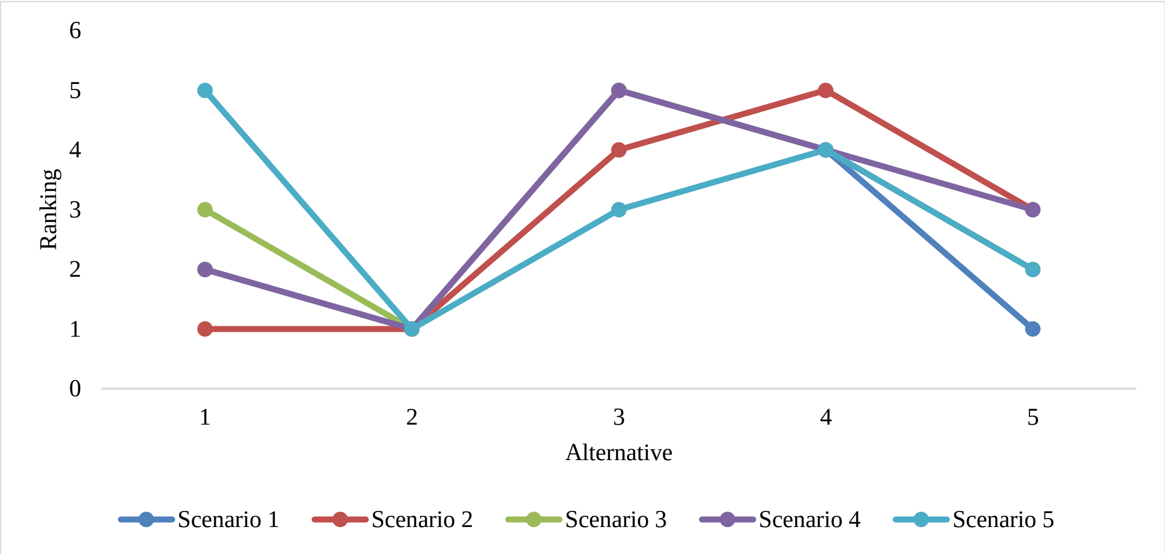

Fig. 2. Sensitivity analysis

4.4. Research implication

This study introduces a new method for determining the optimal co-firing material. In previous studies, the combination of the Fuzzy SWARA-COPRAS method has never been specifically applied in the context of co-firing material selection. This method is designed to assist power plants in identifying criteria, sub-criteria, and biomass alternatives while considering sustainability and supply chain aspects, which have often been overlooked. As such, this method plays a crucial role in supporting companies in transitioning to more environmentally friendly energy, particularly in efforts to reduce carbon emissions from combustion processes.

In addition, integrating these two methods can produce alternative rankings that are more sensitive to changes in policy assumptions and scenarios, as demonstrated through sensitivity analysis. These findings contribute methodologically through the refinement of multi-criteria approaches and have managerial implications for power plant management. Decision-makers can use the results of this evaluation as a basis for developing biomass selection policies that are more adaptive to supply dynamics, environmental risks, and social demands. The use of water in biomass growth and pre-processing, with a weight of 0.070, and supplier availability are crucial considerations in the energy transition framework. This approach provides a solid foundation for developing an energy system that is technically efficient, inclusive, and environmentally and socially responsible.

5. CONCLUSION

This study concludes that applying the Fuzzy SWARA and Fuzzy COPRAS methods is highly relevant in selecting sustainable co-firing with additional supply chain considerations. The study successfully identified several sustainability criteria, including economic, environmental, social, technical, and supply chain aspects, to achieve an energy transition in power plants. The findings of this study can contribute to the management and decision-making of biomass available in Indonesia. This study involved only four experts, whose assessments may not accurately represent all power plants in Indonesia. For future research, it is necessary to consider power plant technologies that account for geographical conditions, which can be utilized as alternative power sources, such as wind power plants. Further research could also increase the number of respondents and add an analysis of the impact of co-firing selection on power plants by integrating other methodologies to obtain more comprehensive results.

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