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Research Article

Improvement of the Sugarcane Agroindustry Supply Chain Sustainability Performance: Lessons Learned from an Empirical Case Study

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Abstract: Indonesia's sugarcane agroindustry plays a crucial role in gross domestic product, yet it faces threats to supply chain sustainability. Empirical studies on selected sugarcane agro-industries are needed to analyse and improve sustainability performance. This study aims to develop a strategy for enhancing the supply chain sustainability performance of the sugarcane agroindustry through performance measurement and empirical case studies. This study employs the fuzzy inference system method, multidimensional scaling, and an adaptive neuro-fuzzy inference system to assess supply chain sustainability performance. This study focuses on economic, social, environmental, and resource sustainability dimensions using 29 indicators. These indicators are subsequently aggregated to evaluate the supply chain's overall sustainability performance. Empirical studies were conducted on two sugarcane agroindustry supply chains to assess the effectiveness of the supply chain and develop strategies for enhancing performance. The sustainability performance of sugar factories by 2023 is almost sustainable and medium sustainable. This study successfully developed lessons learned for sustainability improvement strategies tailored to each agroindustry based on key indicators. Agro-industries are expected to enhance their supply chain sustainability performance and ensure long-term economic, social, and environmental benefits by implementing these strategies. The following lessons were extracted: operational implementation and indicator adjustment, data quality and infrastructure, data pre-processing, and interpretation for managerial decision-making. The methodology for analysing performance and improvement strategies can be implemented to improve the future sustainability performance of the sugarcane agroindustry supply chain.

Keywords: Agroindustry; Sugarcane; Strategy; Supply chain; Sustainability

1. Introduction

Sustainability has become a significant milestone in life and is a primary issue that must be addressed. The United Nations has established 17 Sustainable Development Goals (SDGs) as a commitment to accomplishing a better and more balanced global life. The issue of sustainability has also been widely recognized as a key focus area in development (Brown and Beattie, 2015). Sustainability has been defined as the use of resources for current life without sacrificing future life.

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Sustainability has become a crucial pillar of life and is recognized as a key issue that must be addressed. The United Nations has established 17 Sustainable Development Goals (SDGs) as a global commitment to achieving a better and more balanced life. Many sectors have been applied in business, including manufacturing (Kumar et al., 2022), the service industry and telecommunications (Bakar and Dorasamy, 2023; Grishunin et al., 2022; Nabil and Asrol, 2024), small and medium enterprises (Jayashree et al., 2021), social services (Åhlfeldt et al., 2023), supply chain (Asrol et al., 2023), and agriculture (Kolling et al., 2022). In academia, sustainability has also been emphasized as a critical issue that must be prioritized in development.

Sustainability analysis has been defined and implemented in many sectors, including supply chain management. Supply chain management is a key aspect to consider for sustainability because it involves natural resources that can either have an environmental impact or provide economic and social benefits. Supply chain sustainability is defined as the management of materials, information, and finance through collaboration and information sharing to attain supply chain objectives to meet consumer needs and gain profits by considering economic, social, and environmental balance (Seuring and Müller, 2008). To assess sustainability achievements, the determination of dimensions is not limited to economic, social, and environmental dimensions alone and considers the condition of the industrial business process.

Various studies on sustainability have been conducted extensively. Supply chain sustainability not only focuses on assessment but also on the preparation steps for its implementation. Sustainability in industry is not only about assessment but also about how to maintain and improve sustainability through concrete actions. Many sustainability case studies are currently available for the industry. However, few studies have drawn lessons for further implementation (Ningrum et al., 2022). Therefore, sustainability studies conducted in previous research require a formulation of the lessons learned to derive concrete actions for implementing sustainability in the agro-industry.

Numerous studies have developed sustainability assessment models using fuzzy inference systems (Phillis et al., 2003), system dynamics (Moeis et al., 2020), multi-criteria decision-making, multidimensional scaling (Papilo et al., 2018), and other machine learning methods (Asrol et al., 2021). The crucial aspects of sustainability include the development of models and method analysis and the implementation of the system to provide broad benefits to the community in support of sustainability. A method for analyzing the sustainability performance of the sugarcane agroindustry has also been developed in previous studies, utilizing a multi-methodology approach that incorporates fuzzy inference systems, MDS, and ANFIS (Asrol et al., 2024; Yani et al., 2022).

Studies on sustainability in the sugar supply chain have been widely conducted. (Bantacut and Novitasari, 2016; Gunawan et al., 2018; Gunawan et al., 2019) focused on by-product utilization and environmental impact minimization to develop a more efficient sugar industrial production system based on life cycle assessment (LCA), whereas Bantacut and Aulia, 2019 analyzed the energy requirements for sugarcane harvesting in off-farm activities. Environmental impact assessments within sugar industrial production systems were also conducted by Geethani and Kulatunga, 2024, further confirming that environmentally based LCA approaches are among the most commonly applied methods for evaluating the sustainability of the sugar industry. An important limitation of this study is that environmental and sustainability assessments have generally been conducted separately between processing plants and cultivation activities, resulting in the absence of a more comprehensive analysis that simultaneously integrates both components.

Several studies have also explored supply chain sustainability from organizational and implementation perspectives, highlighting the complex interrelationship between the agricultural (farm) sector and production processes. These studies emphasize the importance of investment support and the adoption of sustainable practices and organizational culture within the sugar industry to enhance sustainability and facilitate the adoption of advanced technologies (Ahmed et al., 2025; Biswas et al., 2024; Mustafa et al., 2025). Beyond the cultural and organizational dimensions, research on supply chain system design has been proposed through the development of supply chain network optimization (Nagasawa et al., 2025) and the design of equitable profit allocation mechanisms among supply chain actors (Asrol et al., 2020; Carvajal et al., 2024).

Collectively, these studies demonstrate diverse perspectives in analysing and designing sugar supply chains, particularly concerning environmental impacts, profitability implications, network design, sustainability performance measurement systems, and organizational culture. Nevertheless, none of these studies have comprehensively developed a sustainability assessment framework equipped with industry-relevant indicators, supported by an adaptive measurement system, and accompanied by an integrated analysis of its operational and sustainability impacts across the entire sugar industry. Building upon prior research conducted by the research team (Asrol et al., 2024; Yani et al., 2022), this study focuses on the implementation of a sustainability assessment model for the sugarcane agro-industrial supply chain. The objective of this study is to derive lessons learned from the implementation of the model to develop a managerial framework for comprehensively enhancing the overall performance of SCS.

This study aimed to implement the sugarcane agroindustry supply chain sustainability assessment model and obtain lessons learned to improve sustainability in other sectors. The model is based on previous research on the sugarcane agroindustry supply chain business process, which incorporates indicator adjustments and in-depth analysis to enhance the SCA supply chain performance. This study contributes to the development of recommendations for implementing practical steps to assess the supply chain sustainability. Based on the findings and lessons learned from implementing the model in the field, this study offers an action plan to enhance supply chain sustainability.

2. Methods

2.1 The Research Stage

The stages of the research are illustrated in Figure 1. This study comprises four main sections: determination of sustainability indicators, supply chain sustainability analysis, action plan formulation, system development for assessing and improving supply chain sustainability, and the lessons learned. This study used the indicators and frameworks developed in previous studies (Asrol et al., 2024; Yani et al., 2022). Several adjustments, including modifications to indicators, preparation of action plans, system development, and empirical studies on the two sugarcane agro-industries to gather direct information from the field, are necessary to provide broader benefits to the community.

2.2 Supply chain sustainability indicators

Sustainability has been assessed in several dimensions but is generally evaluated based on three main dimensions: economic, social, and environmental. This study builds upon previous research on the sustainability of the sugarcane agroindustry supply chain and identifies four key dimensions: economic, social, environmental, and resource (Asrol et al., 2024; Yani et al., 2022). Adjustments and definitions are necessary in sustainability indicators due to differences in business processes, locations, and supply chain configurations between the two agro-industries, as demonstrated by the empirical studies presented in this study. The indicators set in this study must be redefined to consider the business conditions presented in Table 1.

Some adjustment of the indicators needs to be determined: in the previous studies (Asrol et al., 2024; Yani et al., 2022), 28 indicators were identified, whereas in this study, 29 indicators were determined by adding one indicator to the environmental dimension. It is necessary to understand the broader environmental impact and its influence on the supply chain sustainability. Additionally, adjustments to the definition are necessary because of the impact of business processes on empirical studies. Some indicators that are redefined and adjusted for the empirical study include profit allocation, odor and dust disruptions, workplace air quality, planting areas in communities, and responsive sugarcane varieties. These adjustments have been confirmed and validated by academicians and experts in the sugarcane agroindustry through several steps of focus group discussion. Furthermore, other indicators have the same definition as in previous studies and are applied in this study for sustainability assessment and improvement.

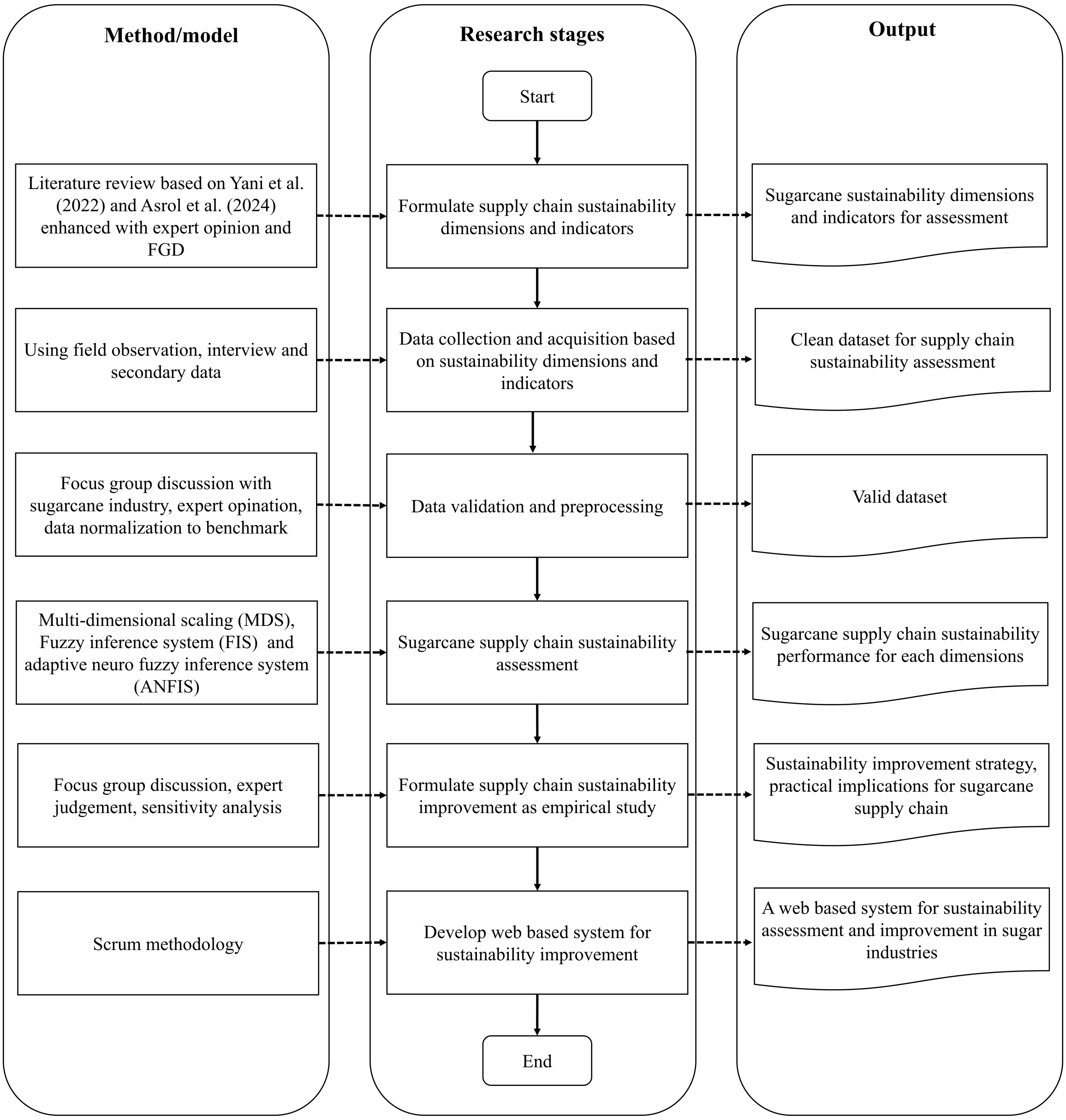


Figure 1 Flowchart of the research steps

2.3 Supply Chain Sustainability Performance Analysis Framework

Figure 2 shows the performance measurement framework of the sugarcane agroindustry supply chain. Sustainability assessment of the sugarcane agroindustry supply chain uses three main models: the fuzzy inference system (FIS), multidimensional scaling (MDS), and adaptive neuro-fuzzy inference system (ANFIS). FIS is used to aggregate certain indicators in each dimension. The FIS was first proposed by (Zadeh, 1965) and facilitates the manage of uncertainty conditions and ambiguity in assessment. Not all dimensions are aggregated with FIS in the proposed research, but only for certain indicators that require information from other sub-indicators. Meanwhile, the indicators that require the FIS model are E2, N1, N3, N4, N5, N6, N7, and R3. The FIS was developed using the Mamdani model with five levels of linguistic labels (Yani et al., 2022).

Table 1 Sustainability dimensions and indicators in two sugarcane agro-industries

D	Indicators	Unit	Definition	Formula
Economic	1. Supply chain risk (E1)	Likert	Level of risk in the supply chain, assessed by experts using a 1-5 scale. The mode value represents the final risk score.	Mode value of the expert assessments (1-5).
	2. Production loss (E2)	%	Sugar production loss is estimated using a fuzzy inference system based on the pol in bagasse, filter cake, molasses, and yield loss.	$f(pol_{bagasse}, pol_{filter\ cake}, pol_{molasses}, yield\, losses)$
	3. Profit allocation (E3)	%	The share of profit retained by the SM after deducting the farmers' profit.	$\left(\frac{profit\ of\ sugarmill - profit\ of\ farmers}{profit\ of\ sugar\ mill}\right) \times 100\%$
	4. Prices of sugarcane farmers (E4)	%	Price received by farmers per ton of sugarcane supplied to the factory.	Secondary data
	5. Reliability (E5)	%	The supply chain's ability to deliver products on time, in the right quantity, and of the right quality.	Secondary data
	6. Return on investment (E6)	%	Percentage of profit earned from total investments.	Secondary data
Social	1. Institutional Support (S1)	Likert	The effectiveness of organizations' support for the efficiency and effectiveness of activities within the agroindustry supply chain, based on expert judgment.	Mode value of the expert assessments (1-5).
	2. Facility support (S2)	Likert	The availability of infrastructure, including roads, electricity, and transportation, supports the supply chain and local communities.	Mode value of the expert assessments (1-5).
	3. Corporate Social Responsibility (S3)	Likert	The perceived benefits of CSR activities for communities and stakeholders.	Mode value of the expert assessments (1-5).
	4. Waste complaints (S4)	Likert	The frequency of public complaints regarding the disposal of industrial liquid waste.	Mode value of the expert assessments (1-5).
	5. Local employment (S5)	%	The proportion of local workers employed in the industry compared to the total workforce based on the number of fixed- and indefinite-term work agreements.	$\left(\frac{Number\ of\ local\ fixed\ and\ indefinite\ term\ work}{Total\ of\ fixed\ and\ indefinite\ term\ work}\right) \times 100\%$
	6. Improvement in partnership (S6)	%	Compared with the previous year, the growth rate of contracted farmland (avalist land) indicates an expansion of partnerships.	$\left(\frac{Current\ year\ avalist\ land - Previous\ year\ avalist\ land}{Previous\ year\ avalist\ land}\right) \times 100\%$

Table 1 Sustainability dimensions and indicators in two sugarcane agro-industries (cont.)

D	Indicators	Unit	Definition	Formula
Environment	1. Odor disruptions and complaints (N1)	PPM	Odor disruptions and complaints are estimated using a fuzzy inference system based on measurements of NH3 and H2S in the surrounding villages.	$f(Amonia,\ hydrogen\ sulfide)$
	2. Dust disruptions and complaints (N2)	PPM	The average number of total suspended particles (TSP) counts in the ambient air of the surrounding villages.	$L2 = Mean(i, j);\ i, j \in TSP\ values$
	3. Electrical emission (N3)	kg CO_2/kg product	Carbon footprint from electricity consumption per product unit, calculated from power use, cane tonnage, and SHS percentage.	$L3 = \left(\frac{a \times b \times 0.001 \times 0.485}{b \times c}\right)$ a: Electricity consumption (kWh/ton cane), b: Cane tonnage (ton), c: SHS (% cane)
	4. Noisy level (N4)	dBA	The noise level was estimated using FIS based on the noise impact inside the production area and the surrounding villages.	$f(Production\ room\ noise,\ Open\ space\ noise)$
	5. Surface water quality (N5)	mg/L	The quality of surface water affected by industrial effluent, estimated using a fuzzy inference system: TSS, BOD_5, COD, and sulfides.	$f(TSS,\ BOD_5,\ COD,\ Sulfide)$
	6. Ambient air quality (N6)	μg/Nm^3	The quality of ambient air around the factory was assessed using SO_2, CO, NO_2, and O_3 levels, using a Fuzzy Inference System.	$f(SO_2,\ CO,\ NO_2,\ O_3)$
	7. Workplace air quality (N7)	Integer	NH_3, dust, NO_2, and SO_2 describe workplace air quality using a fuzzy inference system.	$f(NH_3,\ Dust,\ NO_2,\ SO_2)$
	1. Resource accessibility (R1)	Likert	Access to labor resources ease level with the required quantity and competency, assessed through expert evaluation on a scale of 1 to 5 (Very Low to Very High).	Mode value of the expert assessments (1-5).
	2. Planting area of communities (R2)	%	The proportion of TRI (People's Sugarcane Plantation) area to the total planted land area indicates the level of community involvement.	$\left(\frac{TRI\ planting\ area}{Total\ planted\ land\ area}\right) \times 100\%$
	3. Labor competency (R3)	%	The competency of labor is evaluated based on work productivity and training hours using a fuzzy inference system.	$f(Labor\ productivity,\ Percentage\ of\ training\ hours)$
	4. Sugarcane quality (R4)	Integer	Sugarcane quality was assessed through productivity, yield, and freshness parameters (MBS: Manis Bersih Segar) using a fuzzy inference system.	$f(Sugarcane\ productivity,\ Sugarcane\ yield,\ MBS)$

Table 1 Sustainability dimensions and indicators in two sugarcane agro-industries (cont.)

D	Indicators	Unit	Definition	Formula
Resources	5. Overall recovery (R5)	%	Efficiency of production equipment in sugar production.	Measured directly as a percentage of recovered sugar.
	6. Raw material availability (R6)	%	The raw material sufficiency was assessed by considering the factory's inclusive capacity to process sugarcane.	$\left(\frac{Inclusive\ capacity\ (TCD)}{Exclusive\ capacity\ (TCD)}\right) \times 100\%$
	7. Ratoon level (R7)	Integer	The number of consecutive harvests from a single sugarcane planting without replanting, with the optimal ratoon level being R3 (third ratoon).	Direct observation of the sugar harvest cycles.
	8. Responsive sugarcane variety (R8)	%	The proportion of superior sugarcane varieties in the total planted area identified through interviews with related parties.	$\left(\frac{Superior\ variety\ area}{Total\ planted\ land\ area}\right)$
	9. Mechanization technology (R9)	Likert	Experts assessed the availability of machines and equipment that aid in sugarcane farming and contribute to enhanced sugar content and productivity on a scale of 1 to 5.	Mode value of the expert assessments (1-5).
	10. Raw sugar processing technology (R10)	Ordinal	The technology availability and suitability for processing raw sugar, evaluated based on the technology type: carbonation (lowest), sulfuration, and phosphotation (highest).	Technology assessment: 1: carbonation, 2: sulfitation, 3: phosphatation

Multidimensional scaling is a model that aggregates values across sustainability dimensions. The MDS model has been used in various sectors, not only in the sugar industry but also in the palm oil and bioenergy industries (Papilo et al., 2018). The sustainability dimension framework refers to the model developed in previous studies (Asrol et al., 2024). The challenge in this study is that each dimension has a different number of indicators, therefore, the MDS model developed requires adjusting the benchmark value to ensure that the value of the aggregated sustainability dimension remains stable and consistent. According to (Asrol et al., 2024), the following are the stages to analyze sustainability performance using MDS: (1) calculate the MDS ordination using Euclidean distance (Equation 1), (2) approximate Euclidean distance using regression (Equation 2) and sensitivity analysis using leverage score (Equation 3).

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{1}$$

$$d_{ij} = \alpha + \beta\delta_{ij} + \varepsilon \tag{2}$$

ANFIS was used to aggregate the total value of the supply chain's sustainability. In this study, a more accurate model was developed using the fuzzy c-means algorithm as the model base. The implemented framework follows a data-driven fuzzy representation approach in which fuzzy C-Means-derived membership levels are used as nonlinear feature transformations. Unlike the classical Takagi–Sugeno ANFIS, which constructs combinatorial rule bases, the proposed structure treats fuzzy memberships as enriched feature embeddings and applies neural linear mapping for prediction. This design significantly reduces rule explosion while preserving the capability of nonlinear modeling through fuzzy partitioning. Let the dataset be defined as (x_i, y_i) where x_i denotes the economic, social, environmental, and resource dimensions and y_i be the overall sustainability performance score. The ANFIS is modeled using Table 2.

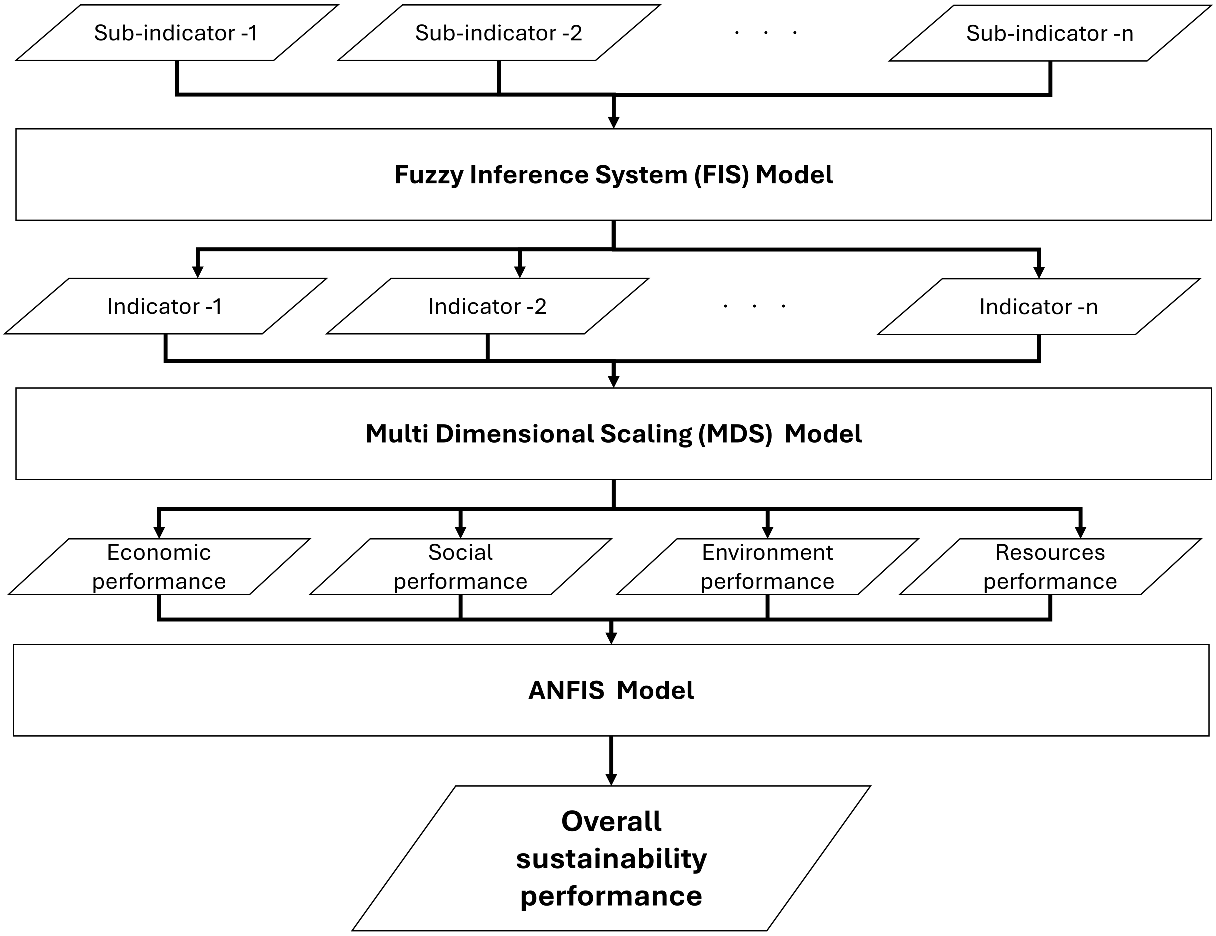


Figure 2 Supply chain performance measurement framework

Table 2 ANFIS model for the sustainability performance analysis

No	ANFIS parameter	Score
1	Membership function	Gaussian
2	Model initiation	Fuzzy C-Means
3	Learning model	Hybrid
4	Epoch	300
5	Error tolerance	0

2.4 Supply Chain Sustainability Improvement Priorities Based on Indicators

An empirical study was conducted to analyze the supply chain sustainability of the sugarcane agro-industry, focusing on two specific agro-industries located in West Java Province, Indonesia. In our previous research, a case study was conducted in the East Java province (Asrol et al., 2024; Yani et al., 2022). Although both companies are located in Indonesia, they have different business processes and cultural characteristics. Previous research has also confirmed that location and culture affect the productivity and performance of any organization (Hung et al., 2022; Zhang and Li, 2016). This empirical study is necessary to confirm and derive lessons to improve the supply chain sustainability of the sugarcane agroindustry.

In this study, the preparation of follow-up actions to improve the sustainability of the sugarcane agroindustry is based on leverage analysis. Leverage analysis enables the identification of the indicators that contribute the most to sustainability improvement (Papilo et al., 2018). Suppose that S_i is the original ordinal score of indicator i, S_ik as ordinal score of indicator i after removal or modification, and n is the number of objects observed. Then, the leverage score (Pitcher and Preikshot, 2001) is defined in Equation 3. A high leverage score indicates that the sustainability score is strongly influenced by the indicator.

Leverage analysis was combined with each indicator's performance score and mapped in a scatter plot. The leverage and performance score are normalized using min-max scaling to map the indicators to Figure 3. Suppose that X is the actual sustainability indicator performance/leverage score, $Xmin$ is the minimum benchmark value of X, and $Xmax$ is the maximum benchmark value of X. Then, the normalization score of indicator X *(Xnorm)* using min-max normalization is stated in Equation 4.

This mapping identifies the indicators with the highest potential sustainability indicators for improving performance through leverage scores but currently exhibit the lowest performance. This mapping is also useful in determining priority indicators and developing action plans to improve medium-term supply chain performance. Figure 3 shows the mapping of the leverage scores and normalized sustainability performance.

An action plan to improve supply chain sustainability was prepared through focus group discussions (FGD). Respondents involved in the FGD came from both academic and practitioner communities to produce action plans relevant to the business process of the sugarcane agroindustry.

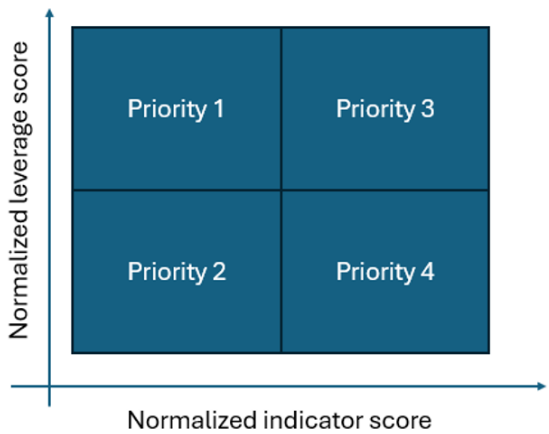


Figure 3 Mapping of sustainability improvement priorities based on indicators

$$Leverage\ Score = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - S_{ik})^2} \tag{3}$$

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{4}$$

2.5 Data collection

This study was conducted in two sugarcane agro-industries in West Java, Indonesia. The collected data are related to the indicators and sub-indicators listed in Table 1. Two types of data were collected: primary and secondary data. Primary data were gathered directly from the source through questionnaires and in-depth interviews. The primary data produce qualitative or linguistic label data to determine each indicator's performance level. Secondary data were collected through field observations, related performance document analysis, and data pre-processing. Secondary data produce quantitative data that require structured preprocessing, normalization, and interpretation to obtain scores for each performance indicator of the sugar-cane agroindustry supply chain.

3. Results and Discussion

3.1 Sugarcane supply chain configuration

Previous studies have widely discussed the supply chain of the sugarcane agroindustry. The sugarcane agroindustry supply chain configuration generally follows that of the food industry supply chain, with the sugar factory serving as the focal company (Ahmed et al., 2025; Asrol et al., 2020). Figure 4 shows the two-sugarcane agro-industrial supply chains examined in this study.

The configuration of the sugarcane agroindustry supply chain categorized into two main functions: primary and secondary actors (Asrol et al., 2017). Primary actors in the supply chain are directly involved in the flow of money, materials, and information, whereas secondary actors are responsible for supporting and ensuring that the supply chain business process runs smoothly. Primary actors in a supply chain involved three groups: suppliers, manufacturers, and distributors. On the upstream side, the supply chain's raw materials are sourced from farmers' sugarcane plantations (Chavez et al., 2020). In contrast to the business process of the sugarcane agroindustry supply chain in East Java, which is mostly fulfilled by independent farmers (Yunitasari et al., 2015), while in West Java are fulfilled by independent farmers but from land with cultivation rights (HGU). The raw materials were sourced from other regions to meet the factory's capacity. This difference in business processes necessitates adjustments to the definitions of the indicators used to measure the performance of the sugarcane agro-industry supply chain in two agro-industries.

According to Chopra et al., 2016, supply chain configuration is categorized into two types based on the initiation of the production process: pull and push systems. The sugarcane agroindustry supply chain is organized into a push system, particularly in the upstream section, to the distribution stage. The sugarcane agroindustry produces sugar from farmers who manage land with cultivation rights (HGU) according to production planning. Sugar factories in Indonesia operate for an average of six months; therefore, they require sufficient raw materials to meet production capacity. After the sugar is produced through a series of processes in the sugar factory, it is sold to distributors through an auction process following the provisions and minimum prices in accordance with government regulations.

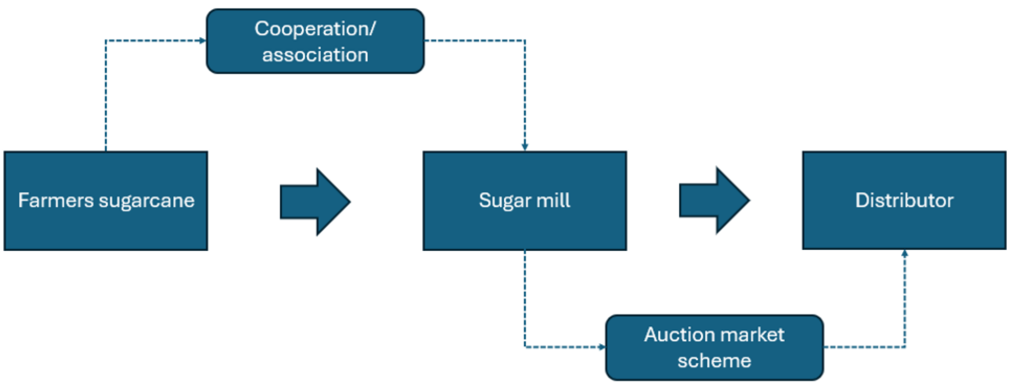


Figure 4 The supply chain configuration of the sugarcane agro-industry

3.2 Supply chain sustainability performance

The supply chain sustainability performance of the sugarcane agroindustry was successfully analyzed and measured in accordance with the methodological framework presented. Supply chain sustainability performance was assessed at two sugar factories, Sugar Factory A and Sugar Factory B, in West Java Province, Indonesia. The results of the supply chain sustainability performance and its categories are referenced in Houshyar et al., 2014 and IUCN, 2001. Table 3 shows the total supply chain sustainability performances for two sugarcane agro-industries, A and B.

Table 3 Performance of supply chain sustainability for sugarcane agro-industries A and B

Dimensions	Year	Agroindustry A		Agroindustry B	
		Index value	Category	Index value	Category
Economic	2021	32.13	Almost unsustainable	16.45	Unsustainable
Economic	2022	24.10	Almost unsustainable	17.89	Unsustainable
Economic	2023	64.51	Almost sustainable	17.18	Unsustainable
Social	2021	70.34	Almost sustainable	48.49	Medium sustainable
Social	2022	49.86	Medium sustainable	47.91	Medium sustainable
Social	2023	70.37	Almost sustainable	51.75	Medium sustainable
Environment	2021	80.83	Sustainable	55.89	Medium sustainable
Environment	2022	76.93	Almost sustainable	76.29	Almost sustainable
Environment	2023	81.06	Sustainable	69.43	Almost sustainable
Resource	2021	71.45	Almost sustainable	72.56	Almost sustainable
Resource	2022	74.15	Almost sustainable	76.93	Almost sustainable
Resource	2023	71.85	Almost sustainable	70.82	Almost sustainable

3.3 Discussion and Lessons Learned

3.3.1 Operational implementation of the indicator adjustment model

The development of a performance measurement model for the sugarcane agroindustry supply chain began in 2022, with the initial framework of the model published by (Yani et al., 2022). The model and indicator framework continues to evolve based on expert input from academics, practitioners, and the broader community. The development of the model and indicators has been published in subsequent publications (Asrol et al., 2024).

To achieve broader benefits for the community, the model must be implemented in the field to improve the sustainability performance of the sugarcane agroindustry supply chain. Several challenges must be addressed during implementation. Initially, the FIS and ANFIS models needed to be adjusted to use the MDS. The use of an FIS is not operational because of the challenges posed by the increasing number of indicators; the rules developed to aggregate dimension values become exponential, illogical, and impractical. The FIS, MDS, and ANFIS models are operational and easy to operate for assessing the supply chain sustainability of the sugarcane agroindustry.

3.3.2 Data quality and infrastructure

Data are the main issue in managing sustainability assessment and improvement. The supply chain of the agroindustry involves many actors and sectors; therefore, data should be collected from multiple sources. In decision-making, data quality is crucial because it affects the conclusion and determines strategy improvements. Therefore, we found that implementing the sustainability performance measurement model must focus on standardization of data forms, availability, privacy, literacy, and model adoption.

1. Data standards. One of the main challenges identified during implementation is the absence of standardized formats across institutions for sustainability-related data. Variability in data structures, including content and format, complicates the integration and analysis. Establishing uniform standards aligned with indicator definitions is critical for ensuring data consistency and comparability across sites and over time.
2. Data Availability. Data availability varied significantly between primary and secondary sources. Secondary data are often fragmented across departments or stored in nondigital formats, limiting immediate accessibility. Primary data collection, especially for qualitative and perception-based indicators, depends on the willingness of knowledgeable stakeholders to participate in interviews and surveys.
3. Data Privacy. Although most of the data used in this study are not highly sensitive, issues of data ownership and access rights occasionally arise, especially when dealing with internal operational data. To maintain trust with stakeholders, all parties must define ethical considerations, including informed consent, confidentiality, and data use agreements.
4. Data Literacy. Data literacy among personnel in the agroindustry sector varies. While some stakeholders possess high analytical competence, others require guidance to understand the sustainability indicators' purpose, structure, and utility. This inconsistency necessitates training or facilitation during data collection to ensure proper comprehension and interpretation.
5. Model Adoption. Adopting the measurement model requires not only technical understanding but also organizational commitment. The model was initially perceived as complex in several implementation settings, particularly when transitioning from the FIS to MDS and ANFIS integration. However, iterative engagement, simplification of operational steps, and visualization of results increase the confidence of stakeholders in using the model.

3.3.3 Preprocessing data for supply chain sustainability assessment

Data preprocessing is the most challenging stage in implementing a model to measure and improve sustainability performance. Resources that are not centralized in the agroindustry require multiple iterations to collect and validate data that matches the indicator definition. Secondary data are collected in large quantities and are in separate documents. This situation is challenging in tracing an accurate and valid dataset. For primary data, in-depth interviews were conducted with the right stakeholders, understanding the problem's context, understanding the dimensions and indicators of sustainability, and maintaining objectivity. This process required time to obtain valid data and information.

Data pre-processing was performed on each sub-indicator and indicator. Preprocessing was performed based on the definition of each indicator, adjustments, and field data collection. In addition to obtaining data in the field, the benchmark obtained from the target or Indonesian national standard is another key aspect that must be defined.

The normalization model was used to standardize data values from various units and scales, enabling equitable comparison and integration across indicators. In this study, min-max Scaling was adopted as the normalization approach because of its ability to transform data into a uniform scale ranging from 0 to 1. Several indicators exhibit inverse relationships, with lower values indicating better sustainability outcomes. For instance, indicators such as production loss potential, air pollution, and water pollution are more desirable when their normalized scores are close to 0. Min-Max Scaling facilitates the comparison of sustainability indicators with different measurement units and magnitudes, which is essential for MDS and FIS analysis.

3.3.4 Interpretation of results for managerial decision making

The supply chain sustainability of the sugarcane agroindustry must be monitored periodically to determine the potential for business sustainability and efforts to improve performance. The results of measuring the performance of the supply chain in two sugarcane agro-industries in West Java Province have shown results that require follow-up prioritization. Figure 5 shows the mapping of supply chain sustainability performance from 2021 to 2023.

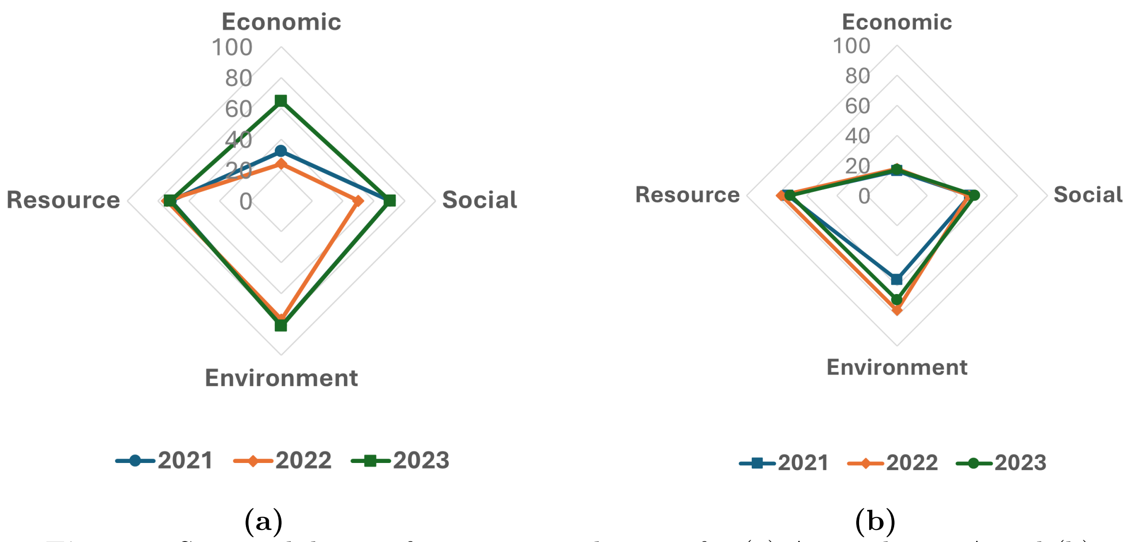
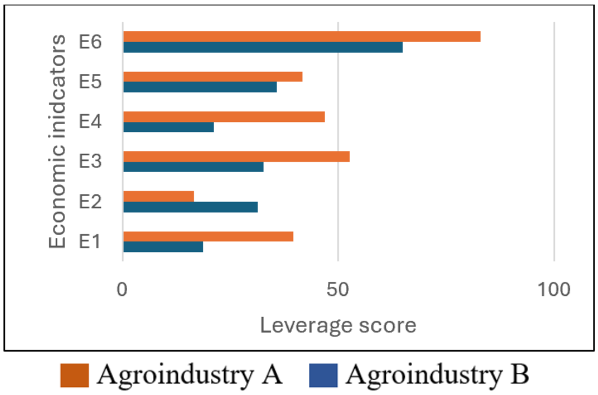


Figure 5 Sustainability performance visualization for (a) Agroindustry A and (b) Agroindustry B

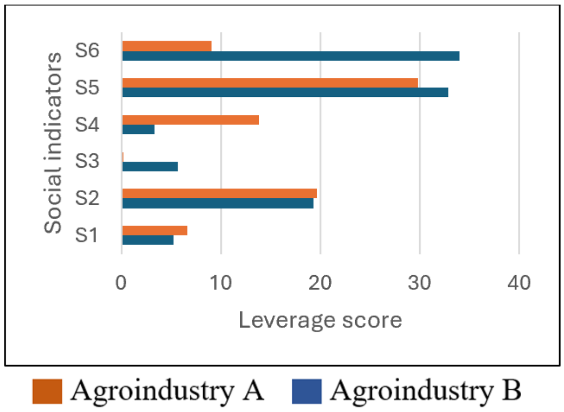
The performance of supply chain sustainability in both industries still shows a value below 75. The results show that in agroindustry A, there are still fluctuations in performance values, especially in the economic and social dimensions. Although the environmental dimension has been consistent, has not yet reached a sustainability target. In agroindustry B, the economic, social, and resource dimensions indicate that the performance value has remained unchanged for the past three years. Regarding the environmental dimension, there is a notable improvement in performance from 2021 to 2023.

Efforts to improve the performance of the sugarcane agroindustry supply chain must focus not only on dimensions but also on the details of sustainability indicators. The sustainability indicators must be determined based on actual field data. Therefore, improving performance can focus on developing follow-up actions based on sustainability indicators. A leverage analysis approach is required for this analysis. Leverage analysis was conducted based on the results of the 2023, following the last assessment of the sustainability performance. Leverage analysis can also identify the contribution index of each indicator to improving sustainability performance, which has been previously explored in previous research (Suardi et al., 2022; Yusuf et al., 2022). Figure 6 shows the leverage analysis of the supply chain sustainability dimension for agro-industries A and B.

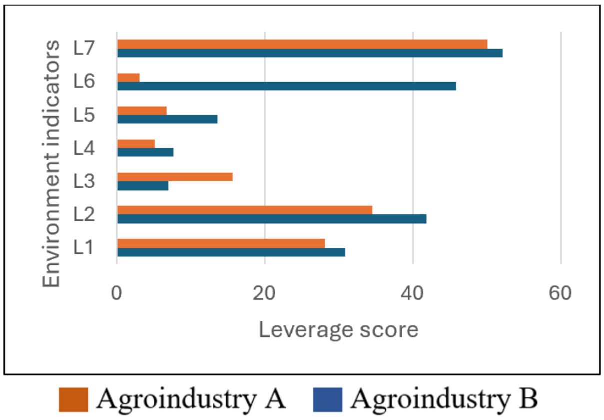
Agroindustry A and agroindustry B have different leverage scores in both sustainability performances. The leverage score indicates the extent to which an indicator provides leverage and its contribution to enhancing sustainability performance. Indicators with high leverage play a significant role to enhance performance in each dimension. The leverage score is also related to the indicator performance. Performance indicators that have already achieved high score should be consistently maintained. In contrast, indicators with relatively low performance require targeted improvement initiatives and strategic interventions to enhance the overall system performance.



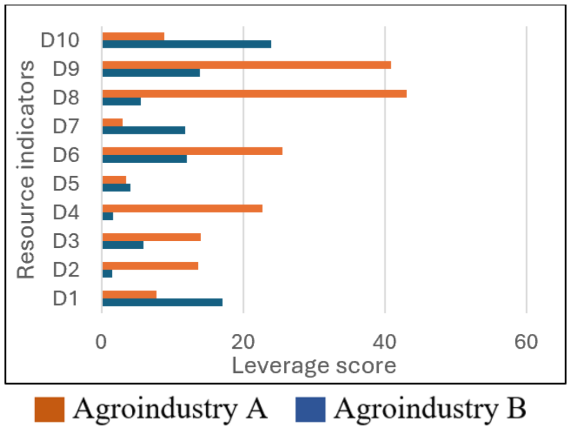
(a)



(b)



(c)



(d)

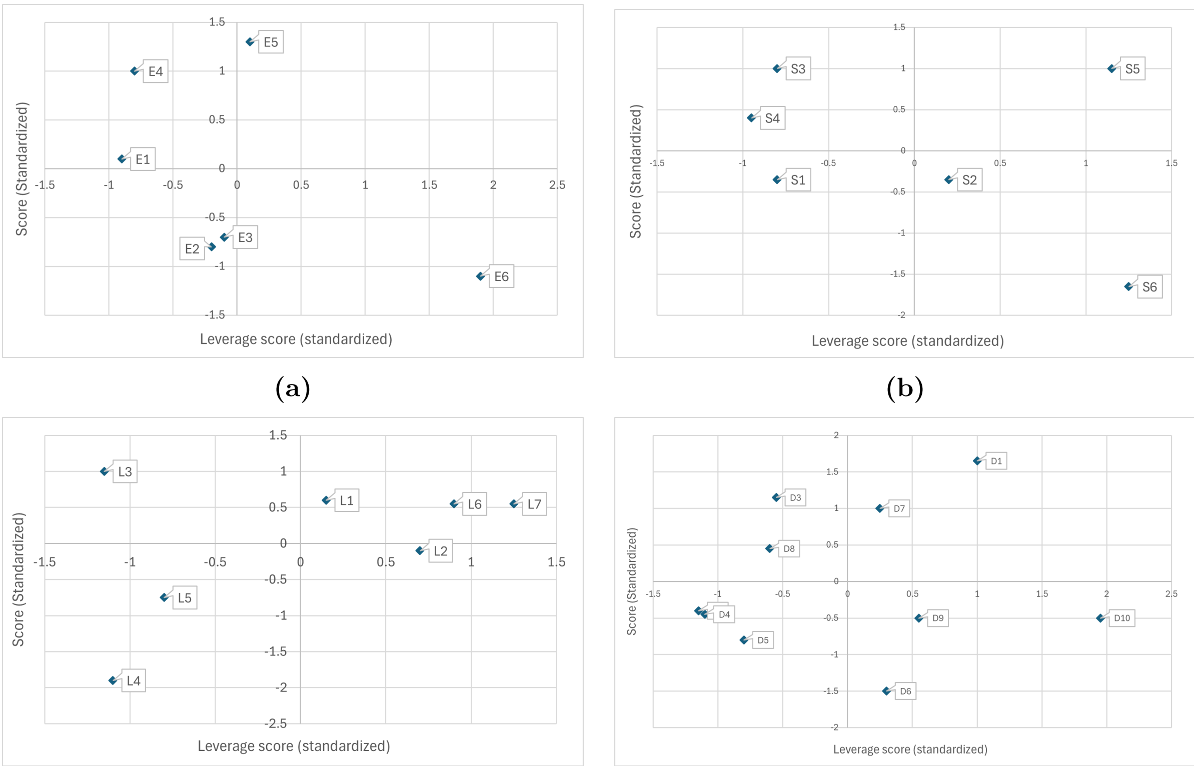
Figure 6 Leverage analysis of supply chain sustainability dimensions based on (a) economic, (b) social, (c) environmental, and (d) resource dimensions

Mapping leverage and performance score is necessary to determine strategies for enhancing supply chain performance. The prepared strategy prioritizes indicators with high leverage and low performance values to positively impact supply chain performance. Figure 7 illustrates the mapping of performance score and leverage of each sustainability indicator. The same analysis was conducted on the results of Agroindustry B to determine the main indicators that need improvement. Based on the analysis and mapping, Tables 4 and 5 present the priority indicators for improving performance.

Table 4 Priority indicators for improving the supply chain performance of Agroindustry A

Dimensions	Indicators	Leverage	Score	Priority
Economic	- E6 (return on investment)	64.98	0	1
Social	- S6 (Increased opt-in stakeholder partnership)	33.98	0.80	1
	- S2 (Availability of infrastructure to support activities)	19.29	49.1	2
Environment	- N2 (facility support)	41.86	71.8	3
Resource	- D9 (Mechanization)	13.9	49.1	1
	- D6 (Sufficient raw materials)	12.03	24.6	2
	- D10 (raw-sugar processing technology)	8.86	49.1	3

The priority of indicators in each dimension becomes the determining point of the action plan to improve the supply chain's sustainability performance. The action plan is developed by current performance, business process, and the potential action plans. The action plan is also based on discussions with experts from academia and practitioners in the sugarcane agroindustry supply chain within focus group discussion (FGD). Three FGD steps were conducted to develop action plan and managerial implications for the industry. Tables 6 and 7 present the recommended action plan to improve performance, based on priority indicators at Agroindustry A and Agroindustry B.



(c) (d)

Figure 7 Leverage mapping and sustainability scores for the (a) economic, (b) social, (c) environmental, and (d) resource dimensions

3.3.5 Comparative Analysis of the Sugarcane Agroindustry Supply Chain Sustainability Performance in East and West Java

Previous studies have discussed the sustainability performance of the sugarcane agroindustry supply chain, which has been published in reputable scientific publications. Various approaches, methods, and indicators have been implemented to assess the value of supply chain performance and to identify potential opportunities for improvement. Two previous studies discussed the sustainability of the sugarcane agroindustry supply chain, as detailed in Table 8.

An increase in the number of sustainability indicators in the sugarcane Agroindustry supply chain can be observed. Initially, there were six indicators in each dimension, which grew to 28 and 29 sustainability indicators, respectively. Adjustments to indicators are considered in accordance with the agro-industry's ongoing business processes and data availability or representation. Adjustment of these indicators is also necessary to enable the assessment of all business activities and supply chains, thereby providing benefits and impacts on the sugarcane agroindustry's sustainability.

The business processes of the sugarcane agroindustry supply chain in Indonesia's provinces of West Java and East Java exhibit distinct characteristics and cultures. For example, in the sugarcane Agroindustry in East Java, smallholder sugar farmers play an important role to supply the sugarcane to the mill through a partnership or outright purchase process. Another phenomenon occurs in the sugarcane agroindustry in West Java, where the majority of raw materials, in the form of sugarcane, are primarily supplied by the sugar industry from land with cultivation rights (HGU), although some are managed by smallholder farmers. The management of plantations and supply chains also has distinct characteristics.

Table 5 Priority indicators for improving the supply chain performance of Agroindustry B

Dimensions	Indicators	Leverage	Score	Priority
Economic	- E6 (return on investment)	83.05	0	1
	- E3 (SCA profit gap)	52.6	0	2
Social	- S2 (Availability of infrastructure to support activities)	19.67	77.2	1
	- S4 (Supply chain waste complaints	13.81	20	2
Environment	- N7 (Workspace air quality)	50.06	88.9	1
	- N1 (institutional support)	28.16	88.4	2
	- N2 (facility support)	34.61	40.5	3
Environment	- D9 (Mechanization)	40.89	49.1	1
	- D4 (raw material quality)	22.77	47.9	2

Table 6 Action plan for improving the supply chain sustainability of Agroindustry A

D	**Priority**	**Indicator**	**Action Plan**
Economic	1	Return on Investment (E6)	Improve cost control and operational efficiency, develop and produce products in line with market trends, and optimize supply chain management.
Social	1	Increased Opt-in Stakeholder Partnership (S6)	Increasing the function and role of cooperatives and sugarcane farmer groups as strategic partners in using credit for productive sugarcane cultivation businesses and sugar bailouts.
	2	Availability of the infrastructure to (S2)	Invest in infrastructure maintenance and improvements, such as access roads for transporting sugarcane and additional irrigation systems.
Environment	1	Workspace air quality (L7)	Installation and maintenance of dust collection devices or blowers to reduce dust spread.
	2	Ambient air quality (L6)	Dust emissions can be controlled by installing a dust capture system or performing additional installation of a scrubber.
	3	Agro-industrial dust disturbance (L2)	Dust emissions can be controlled by installing a dust capture system or performing additional installation of a scrubber.
Resource	1	Mechanization (D9)	Develop a roadmap for revitalization and investment in tools/machines in sugar factory and plantation operations
	2	Sufficiency of raw materials (D6)	A system for procuring parent seeds by sugar factories for wider application according to farmers' needs.
	3	Cane Ratoon Level (D7)	Rejuvenation of sugarcane plants by providing support for superior seeds that are easily accessible to farmers.

The sugar industry periodically monitors the management and administration of plantations on HGU, and most land owned by smallholder sugarcane farmers is managed independently by these farmers. Nevertheless, this does not imply that collaboration with farmers should be disregarded; rather, it must be strengthened.

Table 7 Action plan for improving the supply chain sustainability of Agroindustry B

D	Priority	Indicator	Action Plan
Economic	1	Return on Investment (E6)	Improve cost control and operational efficiency, develop and produce products in line with market trends, and optimize supply chain management.
	2	Supply chain actor profit gaps (E3)	Building fair partnerships through long-term contracts that benefit every supply chain actor.
Social	1	Availability of the infrastructure to support (S2)	Invest in infrastructure maintenance and improvements, such as access roads for transporting sugarcane and additional irrigation systems.
	2	Supply chain waste complaints (S4)	Adequate waste management facilities should be added, especially for liquid and solid waste.
Environment	1	Workspace air quality (L7)	Installation and maintenance of dust collection devices or blowers to reduce dust spread.
	2	Agro-industrial Odor disturbance (L1)	Processing waste more quickly can minimize the occurrence of excessive fermentation in waste.
	3	Agro-industrial Dust Disturbance Level (L2)	Dust emissions can be controlled by installing a dust capture system (dust collectors) or performing additional installation of a scrubber.
Resource	1	Mechanization (D9)	Develop a roadmap for revitalization and investment in tools/machines in sugar factory and plantation operations (short-, medium-, and long-term).
	2	Quality of raw material (D4)	Increasing sugarcane productivity, expanding planting areas with superior sugarcane varieties, and implementing Good Agricultural Practices (GAP) in on-farm and off-farm sugarcane production.

Table 8 Studies on the sustainability of the sugarcane agroindustry supply chain

Aspect	(Yani et al., 2022)	(Asrol et al., 2024)	This study
Dimensions	Economic, social, environmental, and resource	Economic, social, environmental, and resource	Economic, social, environmental, and resource
Number of indicators	24	28	29
The dimensional aggregation method	FIS	MDS	MDS
The total performance aggregation method	ANFIS	ANFIS	ANFIS
Location	East Java, Indonesia	East Java, Indonesia	West Java, Indonesia
Total performance score	68.58	Sugar mill A: 57.2 Sugar mill B: 61.9	Agroindustry A: 70.46 Agroindustry B: 51.81
Methods of performance improvement	The cosine amplitude method	Fuzzy cognitive maps	Leverage and indicator score combination

Referring to (Dania et al., 2022), the sugar industry must consider three primary aspects in enhancing cooperation with farmers in the management of sugarcane cultivation: commitment, power, and adaptation. These three dimensions should be mutually reinforced to achieve the desired quality of sugar raw materials, ensure timely delivery, establish equitable profit allocation, and generate mutual benefits for both parties.

4. Conclusions

The supply chain sustainability of the sugarcane agroindustry requires attention to ensure continuous improvement and increase productivity and business efficiency. Various research models for sustainability analysis have been developed, but the main challenge is the implementation of a model to improve supply chain sustainability. This study implemented a sugarcane agroindustry supply chain performance assessment model, which yielded several lessons learned during the implementation process. In the implementation, 29 indicators and four dimensions of sustainability are the focus of this study: economic, social, environmental, and resource. These are then aggregated into the total performance of supply chain sustainability. The analysis results show that the sustainability performance of sugar factories in 2023 is quite sustainable and less sustainable. This study has also been effective in developing a strategy to improve supply chain performance based on the indicators with the lowest performance and highest leverage. This study provides a comprehensive assessment of supply chain sustainability and an action plan for improving the performance of the sugarcane agroindustry. Moreover, a comprehensive action plan and implementation in the related supply chain operations are required. However, this study has several limitations. First, the analysis is limited to the observed supply chain context and may not fully represent other sugarcane supply chain structures. Second, although the proposed action plan was developed based on field observations and validated through FGD with experts, it has not yet been empirically tested through longitudinal implementation and before-and-after quantitative performance measurement. Potential further research is to develop a comparative analysis of the action plan and strategy implementation for each stage of the supply chain. The before-and-after analysis will make it possible to evaluate the recommendation to produce an iterative strategy in improving the supply chain sustainability performance in the sugarcane agroindustry.

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Author Contributions

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

Data availability statement

The data that support the findings of this study are available on request from the corresponding author

Conflict of Interest

The authors declare no conflicts of interest.

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