RESEARCH ARTICLE

Sustainability performance assessment of sago industry supply chain using a multi-criteria adaptive fuzzy inference model [version 1; peer review: awaiting peer review]

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Abstract

Background: Sustainable supply chains are more competitive than conventional supply chains. Supply chain sustainability performance needs to be carried out to determine sustainability under current conditions and to design appropriate strategies to increase sustainability. This study aims to design a sustainability performance assessment model for the sago agro-industry supply chain and identify critical indicators for sustainability improvement.

Methods: The Fuzzy Inference System (FIS) evaluates sustainability on three levels: economic, social, and environmental. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is then used to aggregate the overall sustainability performance. The cosine amplitude method (CAM) was used to analyze key indicators. This study assessed the sustainability performance on industrial- and small-medium-scale sago agro-industry.

Results: The results show that the supply chain sustainability performance on the industrial scale is 44.25, while it is 48.81 for the small-medium scale with the same status, almost sustainable. Key indicators for improving sago agro-industry supply chain sustainability performance include profit distribution among supply chain actors, institutional support for supply chains, waste utilization (reuse & recycle), and the availability of waste management facilities. The implication of this research for managers regards assessing the current status of sustainability performance and key indicators as a reference for formulating sustainability strategies and practices.

Conclusions: The results of the study will enable supply chain actors to understand the key indicators for improving sustainability performance in the sago agro-industry supply chain, especially in Meranti Islands Regency, Riau Province. The proposed model can be applied to other agro-industries by adjusting the indicators used and...
assessing data availability and suitability for the research object.

**Keywords**
ANFIS models; Fuzzy Inference System; sago agro-industry; sustainable supply chain; sustainability performance
**Introduction**

The Rio Process instituted sustainable development for the first time at the 1992 Earth Summit in Rio de Janeiro (United Nations, 1992). The United Nations General Assembly adopted the Sustainable Development Goals (SDGs) in 2015 (for 2015 to 2030). The Rio Process explains how they are integrated and inseparable from achieving sustainable development at the global level (Parvis et al., 2019). In various fields, such as manufacturing, agriculture, and transportation, there has been growing recognition of the need to adopt sustainable practices. Supply chains are especially important as they impact the entire life cycle of products, from the sourcing of raw materials to the disposal of waste. Supply chains need to prioritize sustainable practices in order to minimize their impact on the planet and ensure a better future for all. A sustainable supply chain is one in which materials, information, and capital work together among stakeholders along the supply chain to achieve the target value of economic, social, and environmental dimensions in response to consumer and other stakeholder demands (Seuring and Müller, 2008). Carter dan Rogers (2008) defines a sustainable supply chain as the strategic, transparent integration and achievement of social, environmental, and economic organizations. Systemic business process coordination between critical organizations aims to improve the long-term financial performance of individual companies’ supply chains.

The concept of sustainable supply chain management (SSCM) is relevant to the sago agro-industry, as it aims to effectively manage the flow of materials, information, and money related to the procurement, production, and distribution of products or services to meet profit and business sustainability (Dubey et al., 2017). A sustainable supply chain model, which is designed to increase the competitiveness of all supply chain stakeholders (Sopadang et al., 2017), can be driven by legal compliance, competitive advantage, cost reduction, economic performance, innovation, social and environmental responsibility, risk management, corporate reputation, quality management, managerial attitude, top management support, team member motivation, government policies, competitors, customers, collaboration with suppliers, pressure from investors, and the influence of NGOs (Emamisaleh and Rahmani, 2017; Engert et al., 2016; Tay et al., 2015). Although sustainable supply chain management is a voluntary effort, business entities cannot ignore the existence of both internal and external incentives. In the case of the sago agro-industry, the supply chain sustainability must be assessed to determine its current performance status and identify tactical steps for supply chain actors to improve supply chain sustainability (Hafezi et al., 2017). This is strategic and essential to supporting food and energy security, as sago palm has huge potential as a source of staple food with little or no competition for fertile land from other food crops, and also for industrial raw materials and renewable energy sources (Ehara et al., 2018). Therefore, sustainable supply chain management can help to ensure the long-term viability and competitiveness of the sago agro-industry.

The sago agro-industry in Indonesia varies from small to large industries. Small industries start with sago farmers who also process sago stalks into sago starch slurry, which medium or large industries will process further. In addition to obtaining raw materials in the form of wet sago starch from processing farmers or small enterprises, large industries also process sago stalks from farmers or traders and their gardens. This condition describes the complex supply chain of the sago agro-industry. Supply chain sustainability assessment involves a multi-dimensional, multi-criterion, and dynamic process. The method chosen for assessing the level of sustainability must accommodate quantitative and qualitative data, the presence of uncertainty, inaccurate and incomplete data, unclear assessments, and characteristics of human evaluation. For this reason, a sustainability assessment model for the supply chain is needed.

A comprehensive supply chain assessment necessitates the use of multiple sources of data. However, information sources have several limitations, including uncertainty, insufficient information, a lack of knowledge on the part of decision makers, and the inability of experts to produce appropriate evaluations (Bappy et al., 2019). In previous research, the number of sustainability indicators was still inaccurate, and the numbers dominated qualitatively. Sustainability assessment also requires qualitative and quantitative indicators to synthesize the opinions of several experts to make the evaluation more comprehensive. The method widely used to assess multi-dimensional sustainability does not accommodate expert opinion, focusing only on output efficiency. The multidimensional scaling (MDS) method has several weaknesses, including the potential to give the wrong indicator score, high subjectivity, the impact of the assessor’s imperfect knowledge on the score, and a scale that requires many objects of comparison for the assessment.

Meanwhile, fuzzy set theory (FST) has an excellent opportunity to be implemented as a basic model in developing a framework for assessing the sustainability of agro-industry supply chains. This model accommodates qualitative and quantitative sustainability indicators that can be completed and combined. Other advantages of FST for evaluating sustainability include adapting to uncertainty, inaccurate and incomplete data, the ambiguity of assessment, and the characteristics of human judgment. In addition, experts and the human mindset readily accept the fuzzy sustainability assessment model. Hence, the evaluation becomes more effective (Houshyar et al., 2014).

This research aims to design a sustainability assessment model for the sago agro-industry supply chain and identify critical indicators for improving sustainability. The study was conducted on the sago agro-industry in the Meranti Islands.
Regency, Riau Province, Indonesia, through observation and interviews. The sustainability indicators are selected on the basis of a review of the literature and expert validation. Sustainability assessment of the economic, social, and environmental dimensions is carried out with the fuzzy inference system (FIS). After the sustainability value of each size is obtained, it is used for the overall sustainability value aggregation using adaptive neuro-fuzzy inference system (ANFIS). The results of the analysis will determine critical sustainability indicators in the sago agro-industry supply chain.

**Methods**

**Research Framework and Stages**

The research framework is divided into four stages: identification of sustainability indicators, FIS modelling, ANFIS modelling, and analysis of critical indicators. The FIS model was created to evaluate the performance of each dimension. The ANFIS model, on the other hand, was used to combine the value of each dimension into the overall supply chain sustainability performance. Figure 1 depicts the research framework.

The research begins with identifying indicators in each dimension, followed by the development of the FIS model to assess the sustainability performance of each dimension, and finally, the aggregation of the sustainability performance of each dimension with the ANFIS model. Furthermore, critical indicators for increasing the supply chain sustainability of the sago agro-industry were analyzed. The stages of the research are shown in Figure 2. The steps of the study are as follows:

**Identification of sustainability indicators**

The first stage of this study is to identify sustainability indicators in the case study on the sago agro-industry. Field observations and a literature review were used to identify sustainability indicators, which were validated through in-depth interviews with practitioners and experts. The indicators that have been selected had to undergo the validation process and critique from relevant experts and stakeholders (Waas et al., 2014). Indicators in each dimension are needed to assess the sustainability level of each dimension. The indicator value of each dimension can be in the form of qualitative or quantitative data.

Sustainability indicators describe and provide information on the sustainability achievements of an organization in each dimension (Juwana et al., 2012). Indicators chosen to assess supply chain sustainability can be viewed from several perspectives, such as environmental impact, social responsibility, and economic feasibility, and must reflect the performance level of the defined sustainability dimensions (Nijkamp and Vreeker, 2000; Waas et al., 2014). Sustainability indicators must be supported by qualitative or quantitative data (Galal and Moneim, 2016; Popovic et al., 2018).

![Figure 1. Research Framework.](image-url)
Sustainability assessment with FIS model

A FIS is a system that is applied to regulate the relationship between the input and output variables of a system. FIS are classified into three types: Mamdani, Sugeno, and Tsukamoto (Castillo et al., 2007). The primary distinction between Mamdani and Sugeno is the outcome of fuzzy rules. As a result of the rule, the Mamdani type employs a fuzzy set, whereas the Sugeno type employs a linear function. The result of each fuzzy rule for the Tsukamoto type employs a monotonic membership function. The Mamdani type was used in this study.

The FIS uses a fuzzification interface to convert crisp input into fuzzy input. After fuzzification, a rule base is developed. Knowledge basis and rule base are interchangeable terms. Finally, defuzzification is used to convert the fuzzy value into the crisp value of the output.

The FIS model’s fuzzification stage represents sustainability indicator data for each dimension. Concerning the target of each indicator, all indicators are scaled with five linguistic levels: very low (VL), low (L), moderate (M), high (H), and very high (VH). If the target is minimal, the linguistic scale will be reversed; very high (VH) will start at the lowest value.
Using a specific membership function, the fuzzification stage converts observed data into fuzzy integers. The membership function in this study is a triangular fuzzy number (TFN). FIS rules are organized in the membership function based on the number of inputs and linguistic levels to produce consequences or outputs. The rule number for each dimension is calculated by multiplying the linguistic levels in the membership function \( m \) by the number of indicators \( n \), as specified in Equation 1. Each sustainability dimension has five indicators, and each indicator has five linguistic levels in the membership function, so 3125 rules on economic, social, and environmental aspects must be written for each FIS model.

\[
\text{Number of fuzzy rules} = m^n
\] (1)

The operator “AND” is associated with the FIS model’s input variables. The FIS model used the Mamdani model, and the output was represented by a linguistic label. Linguistic labels for sustainability performance are classified into five levels: very unsustainable, unsustainable, almost sustainable, sustainable, and very sustainable. To establish the proper output of the fuzzy rule, experts validate the reflection of the relationship of input variables. This study employs approaches proposed by Phillis et al. (2011) to generate output on the fuzzy rules basis.

The fuzzy set with the linguistic scale is assigned an integer value of 1, 2… so on, where one corresponds to the fuzzy set with the lowest sustainability. The fuzzy set VL is assigned a value of 1, L a value of 2, M a value of 3, H a value of 4, and VH a value of 5. Furthermore, each input combination in each rule is summed to get the output value (OV), which is grouped into five linguistic scales.

\[
\text{Output} = \begin{cases} 
\text{very unsustainable, if } 5 \leq \text{OV} \leq 8 \\
\text{unsustainable, if } 9 \leq \text{OV} \leq 12 \\
\text{almost sustainable, if } 13 \leq \text{OV} \leq 16 \\
\text{sustainable, if } 17 \leq \text{OV} \leq 20 \\
\text{very sustainable, if } 21 \leq \text{OV} \leq 25 
\end{cases}
\]

Three thousand one hundred twenty-five rules represented the sustainability dimensions. For example, for rule number 2,675, social sustainability is sustainable if (institutional support is very high) and (local labor absorption is low) and (infrastructure to support activities is low) and (workers’ welfare is very high) and (participation of farmers in partnership is very high). The result is as follows:

Output value (OV) for rule No. 2,675 = 5 + 2 + 2 + 5 + 5 = 19

The FIS model for this study employs the implication method “min” and the aggregation method “max” to evaluate the performance of the sustainability dimension. The method of centroid defuzzification is used. The parameters used to generate the FIS model to evaluate the performance of the sustainability dimension are summarized in Table 1.

**Aggregation of sustainability performance with the ANFIS model**

The FIS and Artificial Neural Networks (ANN) learning benefits are combined in ANFIS. Despite system uncertainty, the FIS rule base describes the relationship between output and input parameters. ANN trains data and finds the best settings for the FIS membership function to get fuzzy rules and membership functions accordingly (Tozan and Vayvay, 2008). ANFIS is a simple data learning technique that converts given inputs into target outputs using a FIS model. Fuzzification, product, normalization, defuzzification, and total output are the five primary process stages in ANFIS operations (Paul et al., 2015). The ANFIS model is structured similarly to the FIS model, except for estimating the membership function parameters and the FIS rules (Abdel-Aleem et al., 2017).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model/method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inference model</td>
<td>Mamdani</td>
</tr>
<tr>
<td>Fuzzy membership function</td>
<td>Triangular Fuzzy Number</td>
</tr>
<tr>
<td>Operator</td>
<td>AND</td>
</tr>
<tr>
<td>Implication method</td>
<td>Min</td>
</tr>
<tr>
<td>Aggregation method</td>
<td>Max</td>
</tr>
<tr>
<td>Defuzzification</td>
<td>Centroid</td>
</tr>
</tbody>
</table>
Several factors must be considered when developing the ANFIS model, including the variable input membership function, the number of training data pairs, epochs, and the model’s error tolerance. In ANFIS modelling, the membership functions (MFs) use grid partitioning by five linguistic MFs (very low, low, medium, high, and very high). Gaussian MFs were used in this model because they accurately describe the data distribution of a real-world problem (Moghaddamnia et al., 2009). The ANFIS learning algorithm combines the least squares estimator (LSE) and error backpropagation (EBP) methods. The model was trained for 10,000 epochs with zero error tolerance. A suitable ANFIS model should have a < 0.1 error (Sun et al., 2015). The parameters used to develop the ANFIS model for aggregating the sustainability supply chain of the sago agro-industry are listed in Table 2.

### Analysis of key indicators

The key indicators should be determined to design a strategic program to increase or maintain supply chain sustainability. Critical indicators are analyzed with the cosine amplitude method (CAM) at this stage. CAM is recommended because it effectively synthesizes fuzzy indicator measures (Ross, 2010). CAM looks for the similarity of data i and data j, symbolized by $r_{ij}$. Data i and j are n data, each having a membership function $m$ in the fuzzy membership function. Each element of a relationship $r_{ij}$ is the result of a pairwise comparison of two data samples, say $x_i$ and $x_j$, where the membership value expresses the strength of the relationship between $x_i$ and $x_j$ is given. The relation matrix will be of size $n \times n$ and, as with all similarity relations, will be reflexive and symmetric — thus, a tolerance relation. The score of the similarity between data i and j ($r_{ij}$) is formulated using Equation 2 and, like all similarity methods, guarantees that $0 \leq r_{ij} \leq 1$ (Ross, 2010).

$$r_{ij} = \frac{|\sum_{k=1}^{n} x_{ik} x_{jk}|}{\sqrt{\left(\sum_{k=1}^{n} x_{ik}^2\right) \left(\sum_{k=1}^{n} x_{jk}^2\right)}}, \text{where } i, j = 1, 2, \ldots, n.$$  

(2)

Next, the value of $r_{ij}$ is arranged into a matrix, and then the average value is searched and normalized to determine the sensitivity value of each indicator. Finally, the value of the key indicators of each sustainability dimension can be determined.

### Collecting Data

Specific sustainability indicators assess supply chain sustainability in the sago agro-industry. This study used 15 indicators with three sustainability dimensions, grouped as qualitative and quantitative data and analyzed using the formula in Table 3. Quantitative data on sustainability indicators were obtained through field surveys, in-depth interviews with supply chain actors, and previous research. Qualitative data was obtained by expert assessment and in-depth interviews with supply chain actors. Supply chain and sago sustainability experts include business actors, academics, and researchers.

This study generated 1,000 data sets using random numbers from zero to 100 by considering all the rules for the input-output relationship to develop the ANFIS model because of the limited availability of actual data. Seven hundred pairs were used for data training, and 300 pairs were used for data testing.

### Verification and Validation Model

This study’s verification and validation model refers to Sargent (2013). The validation procedure ensured the accuracy of the formula and the model. At this point, literature studies back up the FIS model’s sustainability indicators. FIS and

### Table 2. ANFIS model summary.

<table>
<thead>
<tr>
<th>Object Model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input membership function type</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Number of input membership function</td>
<td>5 (Very low, Low, Medium, High, Very high)</td>
</tr>
<tr>
<td>Initiation</td>
<td>Grid partition</td>
</tr>
<tr>
<td>Output membership function type</td>
<td>Linear</td>
</tr>
<tr>
<td>Learning model</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Epoch</td>
<td>10000</td>
</tr>
<tr>
<td>Error tolerance</td>
<td>0</td>
</tr>
</tbody>
</table>
ANFIS model verification ensures the model has the lowest possible error. Experts with knowledge of the model and current real-world conditions perform validation of conceptual models.

The conceptual model is validated by guaranteeing that literature studies justify the sustainability indicators. Fifteen sustainability indicators are used to assess supply chain sustainability performance. All sustainability indicators were determined using field surveys, expert opinions, interviews, and literature reviews. Table 4 shows evidence of verification of sustainability indicators based on a literature review.

FIS and ANFIS model verification is done by evaluating the performance of FIS and ANFIS modelling. The evaluation of the FIS and ANFIS models uses RMSE, the number of membership functions, rules, and error values in training and testing.

Table 3: Supply chain sustainability indicators in the sago agro-industry.

<table>
<thead>
<tr>
<th>No</th>
<th>Dimension</th>
<th>Indicators</th>
<th>Data type</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Economic (E)</td>
<td>Supply chain risk level (E1)</td>
<td>Qualitative</td>
<td>Experts and stakeholder assessment of supply chain risk level</td>
</tr>
<tr>
<td>2</td>
<td>Fair distribution of profit among supply chain actors (E2)</td>
<td>Quantitative</td>
<td>Profit difference between supply chain actors</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>A sufficient supply of raw materials to meet capacity (E3)</td>
<td>Quantitative</td>
<td>The level of adequacy of raw materials is seen from the capacity of the factory</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Product demand difference (E4)</td>
<td>Quantitative</td>
<td>The difference in product demand for this period and the last period</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Market access/marketing network (E5)</td>
<td>Qualitative</td>
<td>Expert and stakeholder assessment of the availability of the product marketing network</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Social (S)</td>
<td>Institutional support for supply chains (S1)</td>
<td>Qualitative</td>
<td>Expert and stakeholder assessment of the level of use of institutions in supporting the efficiency and effectiveness of supply chain activities</td>
</tr>
<tr>
<td>7</td>
<td>Local labor absorption rate (S2)</td>
<td>Quantitative</td>
<td>(Number of local workers/numbers of total workers) x 100%</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Availability of infrastructure to support activities (S3)</td>
<td>Qualitative</td>
<td>Expert and stakeholder assessment of the level of availability of road infrastructure, electricity, docks, ports, and transportation modes to facilitate supply chain activities and the activities of the surrounding community</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Workers' welfare (S4)</td>
<td>Qualitative</td>
<td>Expert and stakeholder assessment of the level of worker welfare</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Increased participation of farmers in partnership (S5)</td>
<td>Quantitative</td>
<td>(Difference in number of farmer logs for this period and last period/last period farmer logs) x 100%</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Environmental (L)</td>
<td>Fuel consumption emissions (L1)</td>
<td>Quantitative</td>
<td>Energy consumption (Terra Joule (TJ)/yr) x Emission factor (kg/TJ)</td>
</tr>
<tr>
<td>12</td>
<td>Water consumption (L2)</td>
<td>Quantitative</td>
<td>Liter/kg product</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Complaints about agro-industrial waste (L3)</td>
<td>Qualitative</td>
<td>Expert and stakeholder assessment of the level of complaints about sago agro-industry waste</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Waste utilization (reuse &amp; recycle) (L4)</td>
<td>Quantitative</td>
<td>Percentage of waste utilized from the total amount of waste generated</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Availability of waste management facilities (L5)</td>
<td>Qualitative</td>
<td>Expert and stakeholder assessment of the availability of waste management facilities</td>
<td></td>
</tr>
</tbody>
</table>
The evaluation of the ANFIS model was carried out using RMSE, which is one of the most popular metrics for evaluating continuous error models. RMSE is a calculation made to find the minor error from the following parameters in the forward step, fix the value of the premise parameter in the backward step with error propagation, and then calculate the error output from the network (Fatkhurrozi et al., 2012). As the name suggests, RMSE is the square root of the mean squared error. RMSE is described in Equation 3 below. \( x_i \) is the prediction value to \( n \), \( y_i \) represents the observed value to \( n \), and \( n \) is the number of the data.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n}}
\]  

(3)

**Results and Discussion**

**Sago Agro-industry Supply Chain and Sustainability Indicators Value**

The goal of any supply chain is to maximize profits from the overall supply chain activity (Chopra and Meindl, 2013). A measure of supply chain success is how thriving activities are coordinated across supply chain levels to create value for consumers and increase profits for each actor in the supply chain (Somashekhar et al., 2014). The supply chain structure describes the boundaries of the supply chain network and represents the prominent members of the supply chain and the roles of each member. In addition, the supply chain structure also explains all the configurations and institutional arrangements or elements in the supply chain that form the network and encourage various business processes. In this research, the supply chain network boundary of the sago agro-industry consists of suppliers, manufacturers, and distributors, which are depicted in the supply chain structure in Figure 3.

Industrial-scale sago agro-industry uses three sources of raw material: sago trunks from sago farmers or traders, sago trunks from factory gardens, and wet sago starch from small-scale wet sago mills. Meanwhile, the small-medium-scale sago agro-industry obtains raw materials only from sago farmers. Distributors will distribute sago starch to retailers or downstream industries.

The sustainability of the sago agro-industry supply chain is assessed on three dimensions: economic, social, and environmental. Fifteen indicators have been selected to assess economic, social, and environmental sustainability based on a literature review, in-depth interviews, and expert validation (Table 4).

Table 5 shows the target, maximum, and minimum indicator values for evaluating the supply chain sustainability performance of the sago agro-industry. The proposed model is built with quantitative and qualitative data (Galal and Moneim, 2016; Popovic et al., 2018). Observations, interviews, and measurements were used to collect quantitative data.
Figure 3. Sago agro-industry supply chain configuration.

Table 5. Indicator value for assessing supply chain sustainability of the sago agro-industry.

<table>
<thead>
<tr>
<th>No</th>
<th>Indicators</th>
<th>Min value</th>
<th>Max value</th>
<th>Target</th>
<th>Data industrial scale</th>
<th>Data small-medium scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Supply chain risk level (E1)</td>
<td>Very low</td>
<td>Very high</td>
<td>Min</td>
<td>0.457</td>
<td>0.487</td>
</tr>
<tr>
<td>2</td>
<td>Fair distribution of profit among supply chain actors (E2)</td>
<td>10</td>
<td>40</td>
<td>Min</td>
<td>36.34</td>
<td>34.58</td>
</tr>
<tr>
<td>3</td>
<td>A sufficient supply of raw materials to meet capacity (E3)</td>
<td>0</td>
<td>100</td>
<td>Max</td>
<td>6.81</td>
<td>64.1</td>
</tr>
<tr>
<td>4</td>
<td>Product demand difference (E4)</td>
<td>-50</td>
<td>50</td>
<td>Max</td>
<td>-22.34</td>
<td>-9.09</td>
</tr>
<tr>
<td>5</td>
<td>Market access/marketing network (E5)</td>
<td>Very low</td>
<td>Very high</td>
<td>Max</td>
<td>0.27</td>
<td>0.23</td>
</tr>
<tr>
<td>6</td>
<td>Institutional support for supply chains (S1)</td>
<td>Very low</td>
<td>Very high</td>
<td>Max</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>7</td>
<td>Local labor absorption rate (S2)</td>
<td>0</td>
<td>100</td>
<td>Max</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>Availability of infrastructure to support activities (S3)</td>
<td>Very low</td>
<td>Very high</td>
<td>Max</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>9</td>
<td>Workers’ welfare (S4)</td>
<td>Very low</td>
<td>Very high</td>
<td>Max</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>10</td>
<td>Increased participation of farmers in partnership (S5)</td>
<td>-25</td>
<td>25</td>
<td>Max</td>
<td>16.18</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>Fuel consumption emissions (L1)</td>
<td>0</td>
<td>0.85</td>
<td>Min</td>
<td>0.48</td>
<td>0.41</td>
</tr>
<tr>
<td>12</td>
<td>Water consumption (L2)</td>
<td>6</td>
<td>40</td>
<td>Min</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>13</td>
<td>Complaints about agro-industrial waste (L3)</td>
<td>Very low</td>
<td>Very high</td>
<td>Min</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>Waste utilization (reuse &amp; recycle) (L4)</td>
<td>0</td>
<td>100</td>
<td>Max</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>Availability of waste management facilities (L5)</td>
<td>Very low</td>
<td>Very high</td>
<td>Max</td>
<td>0.27</td>
<td>0</td>
</tr>
</tbody>
</table>
while expert judgment and a fuzzy membership function were used to collect qualitative data. Qualitative indicators are those that have linguistic labels.

The Performance of the Dimensions of Supply Chain Sustainability

With five indicators as inputs, the FIS model is used to assess the performance of each dimension of sustainability. Using FIS, three models were developed for assessing the economic, social, and environmental dimensions of sustainability. Because each dimension has five indicators, 3,125 rules (5^5 in total) must be created to determine the sustainability performance of every dimension. Figure 4 depicts the fuzzy membership function of the FIS model’s input-output to determine the sustainability performance of the economic dimension.

Figure 4. Membership function of input and output for the economic dimension. a) membership function of input 1. b) membership function of input 2. c) membership function of input 3. d) membership function of input 4. e) membership function of input 5. f) membership function of output.
The consequences of fuzzy rules in this study refer to the methodology proposed by Phillis et al. (2011). Figure 5 depicts the FIS framework for assigning supply chain sustainability performance for the social dimension, while Figure 6 depicts the rule display surfaces. Here are some examples of rules for each of the dimensions generated by the FIS:

1. If (supply chain risk is medium), (profit distribution is high), (raw material supply is very high), (demand is very high), and (market access is medium), then (economic sustainability is sustainable).

2. If (institutional support is medium), (local labor is very high), (infrastructure support is high), (workers’ welfare is high), and (farmers’ partnership is very high), then (social sustainability is very sustainable).

3. If (fuel consumption emissions are very high), (water consumption is high), (waste complaints are medium), (waste utilization is high), and (waste management facilities are very high), then (environmental sustainability is almost sustainable).

Figure 5. FIS model framework for assessing social dimension sustainability.

Figure 6. The fuzzy rules surface.
The Mamdani type with a TFN membership function and a centroid defuzzification function was used to build the FIS model. Experts carry out the validation of the rule base in the FIS model. Following the generation of the FIS model, the data in Table 5 are used to assess the sustainability of each dimension in the industrial- and small-medium-scale sago agro-industry. In the economic, social, and environmental dimensions, the value of the sustainability of the industrial-scale sago agro-industry supply chain was 37.74, 55.29, and 53.17, respectively. Meanwhile, the economic, social, and environmental values of the sustainability of the small- and medium-scale sago agro-industry supply chain were 56.61, 50, and 24.88, respectively. Figure 7 depicts the economic, social, and environmental sustainability of industrial- and small-medium-scale sago agro-industry supply chains.

Yusuf et al. (2019) assessed the sustainability of the sago agro-industry in South Sorong, Papua using the MDS technique with five dimensions and 25 indicators. The difference in indicators used, analytical methods, and research locations will, of course, result in different sustainability performances, so the results of this study cannot be compared. However, the similarity between this study and previous studies is that the value of the environmental dimension is lower than that of the economic and social dimensions. Previous research using the FIS model to assess supply chain sustainability has been carried out by Yani et al. (2022) in the sugarcane agro-industry with four dimensions and 24 indicators.

On the industrial scale, the lowest value is in the economic dimension, while on the small and medium scale, it is in the environmental dimension. The economic dimension indicators with the lowest value for the industrial scale are fair profit distribution among supply chain actors, a sufficient supply of raw materials to meet capacity, and a marketing network. The environmental dimension indicators with the lowest value for the small-medium scale are waste utilization and availability of waste management facilities.

Supply chain risk and fair distribution of profit among supply chain actors are critical indicators for improving the sustainability performance of the sago agro-industry supply chain, on both an industrial and a small-medium scale. Some literature states that agro-industry performance can be improved by efficient supply chain risk management (Safriyana et al., 2019; Septiani et al., 2016; Suripto et al., 2018; Zainuddin et al., 2017). Supply chain risk management uses strategies, techniques, and tools to manage risk along the supply chain to achieve sustainability through collaboration between supply chain members (Mulyati and Geldermann, 2017). One approach to optimizing supply chain risk and mitigation is acceptable risk and balanced profit distribution from the supply chain. It is important to acknowledge the significance of this approach in situations of uncertainty, particularly when working with multiple stakeholders, and to take into account the effects of past collaborative decision-making efforts. As a result, a fair and balanced risk and profit approach seeks to achieve a win-win solution by sharing and distributing profit and risk among all stakeholders to optimize supply chain performance (Chen, 2015; Palsule-Desai, 2013; Qian et al., 2013).

Important indicators in the social dimension are the participation of farmers in partnership and institutional support in both the industrial- and small-medium-scale sago agro-industry supply chains. Cooperation with suppliers has a positive impact on company performance. By reducing transaction costs and obtaining valuable technical resources, a comparative advantage in performance can be achieved through collaboration with suppliers (Wang and Dai, 2018). Previous
researchers have mentioned institutional advantages for supply chains. Astuti et al. (2010) stated that the effectiveness and efficiency of the supply chain in achieving its goals are increased through the identification of needs and institutional structures in the supply chain. Institutions have a significant relationship with two elements, namely, information sharing and collaborative planning, which can increase profits and reduce transaction costs along the supply chain (Kalyar et al., 2013). Institutional is an effort to design interaction patterns so that they can carry out transactions between economic actors and various institutions, such as banks and governments (Alkadafi, 2014). The absence of institutions significantly impacts supply chain performance (Silvestre, 2015). Sustainable performance mitigates the consequences of the collaboration barriers required to establish sustainable supply chain productivity (Kumar and Goswami, 2019).

Important indicators in the environmental dimension are complaints about agro-industrial waste, waste utilization, and availability of waste management facilities. The complaints about agro-industrial waste indicator has the highest value of all the indicators in the environmental dimension. However, the availability of waste management facilities is deficient and even non-existent in the small-medium-scale sago agro-industry. The community around the sago agro-industry that probably causes this are workers who depend on the sago agro-industry for their income. Some are concerned about waste and losing their source of income if the sago factory is closed.

Processing sago palms into sago starch requires water to extract the starch. The processing will produce both liquid and solid waste. Sago stalks are washed, hulled, and grated before being milled or processed for pulping during the sago starch extraction process. A large amount of water is discharged as sago waste during the manufacturing process. The waste is rich in carbohydrates, fiber, suspended solids, unextracted starch, cellulose (fibrous residue from pith), nitrogen compounds, cyano-glucosides, and insoluble fiber. It contains high concentrations of organic matter (such as proteins, lipids, and carbohydrates), is acidic, and emits a foul odor that causes pollution and worsens global environmental quality (Wee et al., 2017). The sago agro-industry, both industrial- and small-medium-scale, must pay attention to indicators L4 and L5 because the content of this waste can worsen environmental quality even though there are no complaints from the community about it.

The Overall Supply Chain Sustainability Performance
Aggregate values must reflect the total supply chain sustainability performance derived from the sustainability performance of the dimension of the previous stage. The ANFIS technique aggregates sustainability performance for each measurement, with three parameters as input: economic, social, and environmental dimensions. The model’s output is the supply chain sustainability of the sago agro-industry. The ANFIS model with grid partition initiation was developed for this study to determine supply chain sustainability performance. The ANFIS model is structured using Gaussian MFs and three input variables, each with five MF levels, resulting in 125 rules that produce one output as the supply chain sustainability performance. The learning process uses 700 data sets and 300 data sets for testing. The data set was trained using a hybrid learning algorithm with 10000 epochs. It can be seen in Figure 8 that the error value significantly decreased

![Figure 8. ANFIS training.](image)
Table 6. ANFIS technical summary.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model/function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input MFs type</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Output MFs type</td>
<td>Linear</td>
</tr>
<tr>
<td>Number of input MFs</td>
<td>5, 5, 5</td>
</tr>
<tr>
<td>Learning method</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Epochs</td>
<td>10000</td>
</tr>
<tr>
<td>Number of rules</td>
<td>125</td>
</tr>
<tr>
<td>Training error</td>
<td>0.007267</td>
</tr>
<tr>
<td>Testing error</td>
<td>0.009306</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.009592</td>
</tr>
</tbody>
</table>

at the 0-4000th epoch and resulted in the smallest error value at the 8300th epoch with a value of 0.007267. Table 6 shows a summary of the parameters and factors considered for developing the ANFIS model for the aggregation of the overall supply chain sustainability performance of the sago agro-industry.

ANFIS training is critical for creating a model and determining the parameters with the least error. The ANFIS model’s training data have an error of 0.007267, while the test data have an error of 0.009306. The error condition for model training is < 0.1 (Sun et al., 2015). RMSE was also used to test the ANFIS model. With an RMSE value of 0.009592, the RMSE parameters for ANFIS performance evaluation show that the ANFIS model performs well. The RMSE value of 0.009592 indicates that the average predicted value differs from the actual value by 0.009592. Based on the performance evaluation, the ANFIS model can accommodate the aggregation of the supply chain sustainability of the sago-agro-industry.

Figure 9 depicts the ANFIS model’s MFs following the training process. The MFs scale changes dynamically at each linguistic level, indicating that the model accurately reflects the training data. Figure 9 demonstrates the importance of training data in configuring MFs to predict the output. As a result, compared to the previously mentioned ANFIS model, the ANFIS model with grid partition can aggregate overall supply chain sustainability performance with near-zero errors.

ANFIS successfully designed three input dimensions of sustainability and one output from aggregating the total supply chain sustainability performance by launching the grid partition model. Figure 10 depicts the ANFIS model’s architecture. Finally, the ANFIS model is used to aggregate the overall sustainability performance of the supply chain. This study validates the performance of the sustainability dimension by aggregating the overall supply chain sustainability performance using the ANFIS model. The validation results show that the industrial-scale sago agro-industry supply chain sustainability performance is 44.25, while the small-medium-scale sago agro-industry is 48.81. Both companies’ supply chains are in the almost sustainable category. Verification of the ANFIS model is performed to aggregate the overall supply chain sustainability performance using an error value.

The ANFIS model has also been used to assess country sustainability (Nilashi et al., 2018; Tan et al., 2017). The number of inputs, data sets, membership functions, and epochs strongly influences the lowest error value achieved in the training process.

The advantage of the sustainability performance assessment model using the FIS and ANFIS techniques is that it can be used repeatedly to assess sustainability performance regularly by ensuring that indicators and ranges of values are still relevant. Managers must measure sustainability performance periodically to develop an action plan (Sharma et al., 2021).

Analysis of Key Indicators

Key indicators are analyzed using the CAM approach to determine which ones can significantly improve sustainability performance. Key indicators need to be sought for each dimension of sustainability, economic, social, and environmental. CAM shows that indicators with high values are key indicators that should be used to improve sustainability performance.

The critical indicators in industrial- and small-medium-scale sago agro-industry supply chains are slightly different. The key indicators of the economic dimension in the industrial-scale sago agro-industry supply chain include fair distribution
of profit among supply chain actors (E2), differences in product demand (E4), and market access/marketing networks (E5). In the small-medium scale, they are E4, supply chain risk (E1), and E5. The critical indicator E2 is in line with previous research on the supply chain of the coffee, cocoa, and sugarcane agro-industry, which states that fair profit sharing, is the primary indicator of the economic dimension (Jaya et al., 2013; Sriwana et al., 2017; Yani et al., 2022). Figure 11 presents the key indicators of the economic dimension in the supply chain of the industrial- and small-medium-scale sago agro-industry.

The key indicators of the social dimension in the industrial-scale sago agro-industry supply chain include the availability of infrastructure to support activities (S3), institutional support for supply chains (S1), and workers’ welfare (S4). In the small-medium-scale industry, they are S4, S3, and S1. Although the values and order of the key indicators in the industrial scale and the small-medium scale are different, the key indicators of the social dimension in both industrial scales are the same, namely, S1, S3, and S4. The S1 indicators need to be improved, considering their shallow values may not even exist to improve the sustainability performance of the sago agro-industry supply chain. The critical indicator S1 is in line with previous research on the cocoa and sugarcane agro-industry supply chain, which states that institutional support is the

![Figure 9. Membership function of the ANFIS model before (a) and after (b) the training process.](image-url)
primary indicator of the social dimension (Sriwana et al., 2017; Yani et al., 2022). Figure 12 shows critical indicators of the social dimension in the supply chain of the industrial- and small-medium-scale sago agro-industry.

The key indicators of the environmental dimension in the industrial-scale sago agro-industry supply chain are fuel consumption emissions (L1), availability of waste management facilities (L5), and water consumption (L2). In the small-medium scale, they are L2, waste utilization (reuse & recycle) (L4), and L1. All indicators used to assess the sustainability of the environmental dimension are critical. The indicators that still need to be improved by the two scales of the sago industry are L4 and L5, which are currently very minimal and have not even been carried out in the small-medium scale sago agro-industry. Previous research on the coffee and sugarcane agro-industries supply chain has also stated that it is a significant indicator of the environmental dimension and needs more attention (Jaya et al., 2013; Yani et al., 2022). Figure 13 shows the critical indicators of ecological measurements in the supply chain of the industrial- and small-medium-scale sago agro-industry.

The results of the analysis of key indicators are the critical indicators that, if the value is increased, will significantly improve sustainability performance. Analysis of these key indicators is needed to formulate strategic and action plans to improve sustainability performance. Key indicators for improving sustainability performance in each dimension include fair profit distribution among supply chain actors, institutional support for supply chains, waste utilization (reuse & recycle), and availability of waste management facilities.
Managerial implication

The sustainability performance assessment model for the sago agro-industry was developed using carefully chosen indicators that are relevant to the industry. The sustainability of the sago agro-industry supply chain must be carried out jointly by all actors in the supply chain. To find out the sustainability status, managers at focused companies can periodically assess the sustainability performance of the supply chain. The advantage of the sustainability performance assessment model using FIS and ANFIS is that it can be used frequently and updated regularly. Identifying critical indicators helps managers develop strategic plans and practices to improve sustainability performance.

Conclusions

Based on FIS and ANFIS, this study develops a two-stage sustainability assessment model for the sago agro-industry supply chain. The proposed sustainability assessment model is accurate and can be used based on model verification and validation results. The developed FIS model can evaluate the supply chain sustainability performance of the industrial- and small-medium-scale sago agro-industry in all dimensions. The supply chain sustainability performances in the economic, social, and environmental dimensions of the industrial-scale sago agro-industry are 37.74 (unsustainable), 55.29 (almost sustainable), and 53.17 (almost sustainable), respectively. In the small-medium scale, the scores are 56.61 (almost sustainable), 50 (almost sustainable), and 24.88 (unsustainable), respectively.

ANFIS model has grid partition initiation that incorporates supply chain sustainability performance across all dimensions. The ANFIS model has close to zero training and testing errors, implying that it was able to assess supply chain
sustainability performance with good results. The validation process reveals that the supply chain sustainability performance of the sago agro-industry is 44.25 in the industrial-scale industry and 48.81 in the small-medium scale, with a sustainability status of almost sustainable. In addition, key indicators for enhancing supply chain sustainability performance are examined in this study. Key indicators for improving the sustainability performance of the sago agro-industry supply chain include profit distribution among supply chain actors, institutional support for supply chains, waste utilization (reuse & recycle), and the availability of waste management facilities.

The model presented in this study for assessing the sustainability of the sago agro-industry supply chain is limited to three dimensions: economic, social, and environmental. Further research may add other dimensions, such as resources or technology. Considering data availability, only five indicators are used in each dimension. The proposed model can be applied to other agro-industries by adjusting the indicators used and assessing data availability and suitability for the research object.

Fair profit distribution among supply chain actors is the key indicator of the economic dimension, and further research on the proper profit distribution model is needed. In addition, research on institutional strengthening of the sago agro-industry supply chain is also required to accommodate the critical indicators in the social dimension. Finally, it is also important to formulate a strategy for waste management (reuse & recycle) and identify the facilities that are needed by considering the environmental impacts and costs involved.

**Ethical statement**
This study has been approved by The Head of Agroindustrial Engineering Postgraduate Program at Bogor Agricultural University, under the approval number: 770/IT3.6.3/KM/M/B/2023. Informed written consent was collected from each participant.

**Data availability**
This data consists of two data sets to create a sustainability assessment model and analysis code written in GNU Octave:


This project contains the following underlying data:

1. Dataset for train ANFIS model.csv (Data set for model learning)
2. Dataset for test ANFIS model.csv (Data set for model testing)
3. Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

**Software availability**

1. Economic_dimension.m (Analysis code for economic dimension)
2. Social_dimension.m (Analysis code for social dimension)
3. Environmental_dimension.m (Analysis code for environmental dimension)
4. Aggregation.m (Analysis code for aggregation)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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