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Sustainability of smallholder oil palm plantations: A study in Riau, Indonesia

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Abstract: Oil palm plantation is a strategic commodity for the national economy and the welfare of communities. Smallholder oil palm plantations, as part of the palm oil supply chain, are facing sustainability matters. This study aims to assess the index and status of sustainability across the social, economic, environmental, technological, and institutional dimensions, as well as identify sensitive attributes affecting the sustainability of smallholder oil palm plantations. The index assessment utilized the RAP-ISPO method through MDS. The MDS analysis covers all of the aforementioned dimensions. The study was conducted in two major oil palm plantation sub-districts in Riau Province, including Dayun and Mempura. This study used both primary and secondary data. Primary data were gathered through interviews, surveys, and observations. Secondary data were sourced from relevant agencies such as the Central Statistics Agency, Siak Agricultural Office, and related research articles or reports. The respondents were 203 farmers, who were selected purposively. The multidimensional sustainability index analysis of oil palm plantations in Riau has yielded an overall sustainability index of 63.30, which falls into the "sufficiently sustainable" category. The sustainability indices for the five dimensions are as follows: economic (60.85%), social (67.54%), environmental (53.91%), technological (71.70%), and institutional (62.51%). The technological dimension has the highest index value, while the environmental dimension has the lowest. Overall, each dimension falls into the "sufficiently sustainable" category, with varying index values, indicating the need for different policies to evaluate the sustainability of smallholder oil palm plantations in Riau.
Keywords: *Economic, Environmental, Multidimensional scaling (MDS), Social, Sustainable agriculture.*

1. Introduction

Oil palm is a main export commodity with numerous advantages for the Indonesian economy. The development of oil palm plantations began in 1969 when the government established state-owned plantation companies with an initial investment from the World Bank and the Asian Development Bank. Since the early growth of the oil palm industry in Indonesia in the 1970s, plantations have been predominantly owned by private enterprises. There are three types of oil palm plantation concessions in Indonesia: smallholder plantations, state-owned large plantations, and privately-owned large plantations [1].

To support economic development by growing foreign exchange through export, one of the plantation commodities that plays a significant role in Indonesia's economy is oil palm. It is one of the most extensively cultivated plantation crops in Indonesia. The plantations also offer numerous benefits. First, oil palm produces palm oil as a raw material for various food and non-food products. Secondly, it is the most cost-effective source of vegetable oil compared to other oil-producing plants. Thirdly, it is highly suitable for cultivation in numerous areas nationwide. These make oil palm a crucial vegetable oil producer in the global oil industry [2].

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Oil palm plantations in Riau remain the prime producers of palm oil in Indonesia, covering an area of 2.87 million hectares, or 18.70% of the total oil palm plantation area in the country. This vast area allows Riau to produce 8.74 million tons of crude palm oil (CPO) [1]. However, the rapid expansion of oil palm plantations also brings significant environmental, social, and economic challenges. The global request for palm oil drives land use changes, contributing to increasing environmental, social, and economic challenges. These challenges include concerns about deforestation, soil degradation, and the loss of ecosystem services, along with related impacts such as land grabbing, food price instability, income inequality, and land conflicts related to palm oil concessions [3, 4]. Sustainable cultivation practices are vital to safeguard that palm oil production supports economic development and poverty alleviation in tropical regions while lessening undesirable environmental and community effects. In summary, the route to sustainable palm oil encompasses balancing economic benefits with environmental and social considerations [5].

Although palm oil plantations are believed to make significant contributions to regional development and the national economy, smallholder oil palm plantations are fragments of the palm oil agribusiness supply chain that is increasingly essential to adopt sustainability aspects. Ensuring sustainability in these plantations is challenging, as economic motives govern the cultivation practices. However, this should not deter policymakers from striving to achieve sustainable smallholder palm oil plantations [6]. This demand is addressed through the Indonesian Sustainable Palm Oil (ISPO) certification. The ISPO certification aims to promote CPO and improve the image of Indonesian palm oil [7]. Certification of oil palm plantations is one mode to mitigate environmental, economic, and social impacts, as well as global warming, the extinction of endangered species, and other issues associated with oil palm cultivation. It also assists farmers in complying with requirements for exporting sustainable palm oil.

Most research on oil palm plantation sustainability has focused primarily on three main dimensions, including economic, social, and environmental, often providing only a general overview of sustainability levels. For instance, studies on the sustainability of oil palm-based biodiesel typically address its sustainability status through these three dimensions. However, with changing times, there is a need for a broader sustainability assessment that also considers technological and institutional dimensions to evaluate sustainability more effectively [2].

This study scrutinizes sustainability across five dimensions: social, economic, environmental, technological, and institutional. These dimensions are utilized to assess the sustainability of oil palm plantations as a livelihood for local communities. The sustainability indicators employed in this research are based on the values and standards of the ISPO certification. Therefore, designing sustainable oil palm plantations for smallholders is essential to achieving sustainability from various dimensions. This approach aims to enhance economic growth, promote social equity, and improve environmental management and governance. Appraising sustainability is crucial as it helps evaluate whether a plantation is making progress or facing challenges over a specific period.

This study aims to weigh the index and status of each dimension—social, economic, environmental, technological, and institutional—and to identify sensitive attributes that influence the sustainability of smallholder oil palm plantations.

2. Materials and Methods

The research location was selected using the purposive sampling method, focusing on the Riau Province, specifically in the Dayun and Mempura sub-districts. Farmers were chosen as samples through purposive sampling with two main criteria: 1) oil palm plantation farmers who are members of cooperatives or farmer groups, and 2) farmers who own oil palm plantations ranging from 2 to 4 hectares. The study encompassed 203 farmers in either farmer groups or cooperatives.

Both primary and secondary data were used. Primary data were gathered directly over interviews, surveys, and observations. Secondary data were obtained from related agencies such as the Central Bureau of Statistics, the Siak Agricultural Office, the Agriculture and Food Security Office of Riau Province, and the results of related studies, including articles or reports from relevant institutions. The data were collected using several techniques, including surveys and interviews. Surveys were done by

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distributing questionnaires to attain quantitative data. The questionnaires were given to respondents to respond to questions linked to the research topic. Interviews focused on in-depth discussions with participants from farmer groups and cooperatives, managers of farmer group associations and cooperatives, village heads and officials, and non-governmental organizations.

The study utilized multi-dimensional scaling (MDS) analysis formulated by the Fisheries Center at the University of British Columbia. The MDS analysis aimed to assess the sustainability of smallholder oil palm plantations in Riau Province, centering on the economic, social, environmental, technological, and institutional dimensions. This was achieved using the RAP-ISPO (Rapid Appraisal-Index Sustainability of Palm Oil) technique, modified from the Rapid Appraisal Technique for Fisheries (RAPFISH) program. The modifications involved developing or altering indicators for each dimension or attribute to align with the system, topic, and scope of the research [8].

The sustainability analysis was conducted through several stages: (1) determining the attributes (29 attributes were grouped into five dimensions, including 5 economic, 6 social, 7 environmental, 6 technological, and 6 institutional dimensions); (2) grading each attribute on an ordinal scale following the sustainability criteria of each dimension, from 1 (poor) to 3 (good) or according to the attribute's characteristics; (3) data analysis using the RAP-ISPO technique, processed with RAPFISH software (version 1.0) as an add-in in MS-Excel, which involved organizing the indicator scores into a Rap Scores matrix within an MS-Excel worksheet; 4) assessing the index values and sustainability status both multidimensionally and within each dimension; (5) evaluating sensitive variables affecting sustainability using leverage analysis; and (6) weighing the impact of calculation errors using Monte Carlo analysis.

Leverage analysis was performed to identify sensitive indicators that influence sustainability. This analysis in MDS was to determine the key indicators. These indicators were identified based on the leverage analysis results, as observed in the changes in Root Mean Square (RMS) ordination along the X-axis. The greater the RMS change, the more sensitive the indicator is to improving sustainability status. Subsequently, Monte Carlo analysis—an uncertainty analysis—was carried out. The analysis was to estimate the impact of random errors in the analysis process within a 95% confidence interval. In this context, Monte Carlo analysis served as a simulation method to evaluate the impact of random errors across all dimensions. The output was presented as a Monte Carlo index and then compared to the index value from the MDS analysis. A small difference between the two index values indicates several aspects [9] including:

a. The assessment error for each attribute is relatively minor.
b. The variance in evaluation is relatively low.
c. The repeated analysis process is stable.
d. Data entry errors and losses can be prevented.

The results of the MC analysis and the MDS analysis were compared with a 95% confidence level, resulting in differences in the values between those analyses of either greater (MC-MDS > 5%) or smaller (MC-MDS < 5%). If the difference exceeds 5%, the MDS analysis results are inadequate for assessing the sustainability index. Conversely, if the difference between both analyses is less than 5%, the MDS analysis results are adequate for evaluating the sustainability index [10]. The goodness of fit reflects the magnitude of the S-stress value and the coefficient of determination (R^2). A good model is indicated by an S-stress value of less than 0.25 (S < 0.25) and an R^2 close to 1. The estimated score for each dimension is expressed on a scale ranging from the worst (bad) at 0% to the best (good) at 100%. The scores were examined using RAP-ISPO to decide the sustainability status as follows.

Table 1.
The scale of the sustainability status index.

Sustainability index scale (%)	**Sustainability status**
0.00 – 25.00	Not sustainable
25.01 – 50.00	Less sustainable
50.01 – 75.00	Moderately sustainable
75.01 – 100.00	Sustainable

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3. Results

3.1. Social Dimension Sustainability Index and Status

The social dimension is critical for sustainable smallholder oil palm cultivation. This dimension is one of the key pillars of sustainable development, contributing to rural development and poverty alleviation.

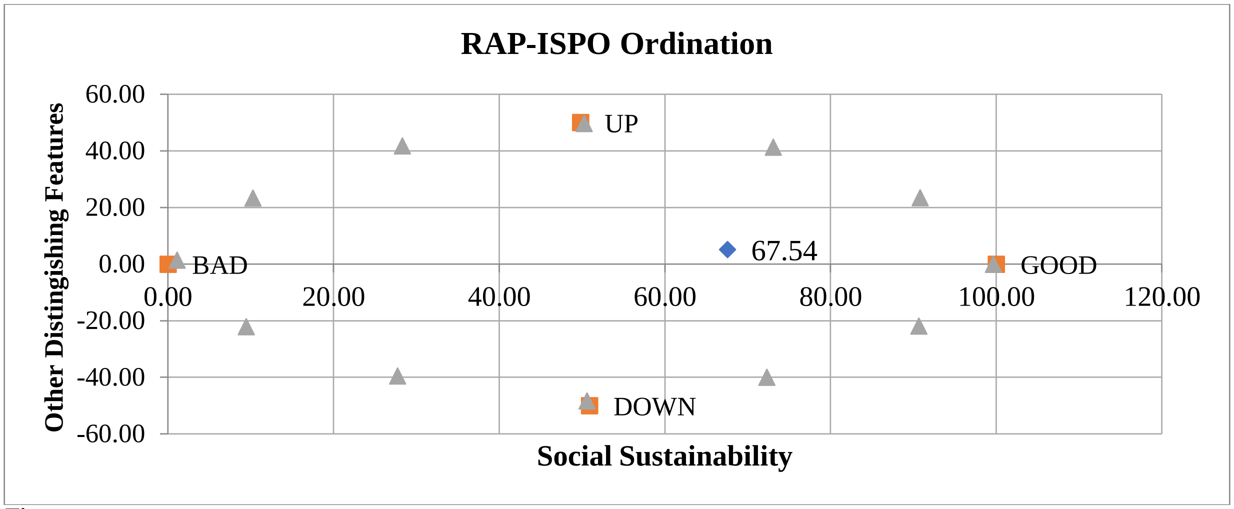

Figure 1.
RAP-ISPO social dimension.

Grounded on the RAP-ISPO analysis, the sustainability index for oil palm plantations in Riau Province reached a value of 67.54% for the social dimension, falling into the 'moderately sustainable' category. This indicates that the community life in Riau Province fairly supports the management of palm oil farming operations.

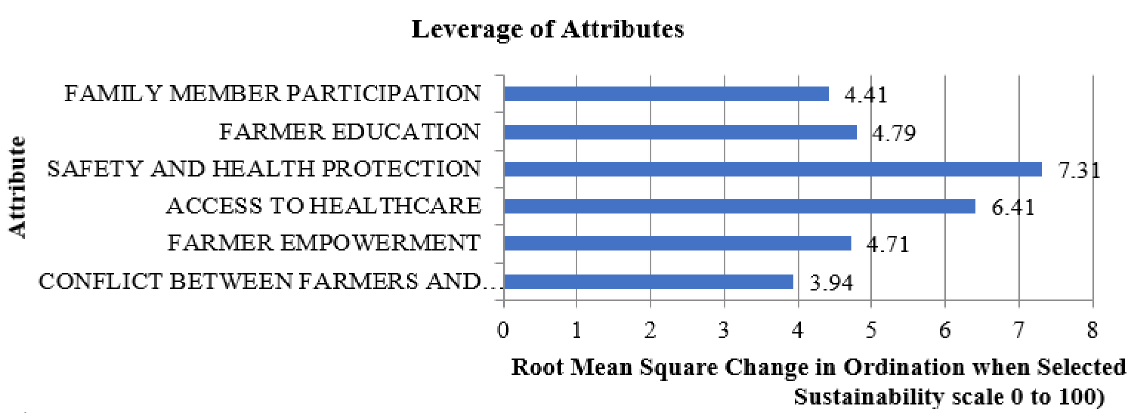

Figure 2.
Leverage analysis of the social dimension.

3.1.1. Sensitive Attributes Affecting the Social Dimension

The leverage analysis results show that occupational safety and health protection (RMS = 7.31), access to healthcare (RMS = 6.41), and farmer education (RMS = 4.79) are the most sensitive to improvements in the sustainability status of the social dimension. These indicators reflect that the social dimensions, including occupational safety and health protection, access to healthcare, and farmer education, are sufficient to support the sustainability of the palm oil industry in the area. Leverage analysis was to identify the attributes most sensitive to prompting the sustainability of the social

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dimension of oil palm plantations. The larger the change in RMS value, the more sensitive the attribute's role is in improving the sustainability status.

3.2. Economic Dimension Sustainability Index and Status

The economic dimension represents farmers' ability to meet their needs sustainably. Smallholder oil palm plantations are considered good or sustainable if they are able to advance the economic well-being of the farmers.

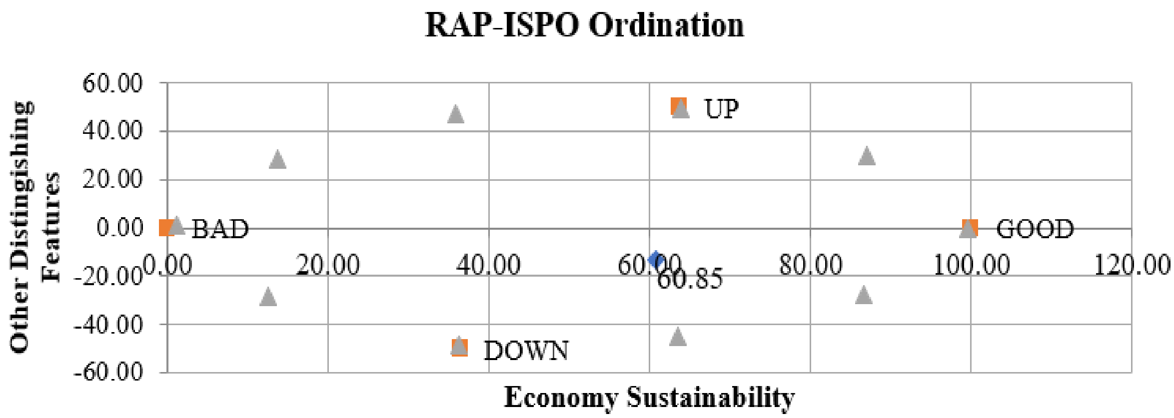

Figure 3.
RAP-ISPO economic dimension.

Based on the RAP-ISPO analysis, the sustainability index for the economic dimension was 60.85%. This indicates that economic activities within the oil palm plantation sector somewhat support the local economy. However, improvements and attention are needed, particularly regarding attributes that are still not optimal.

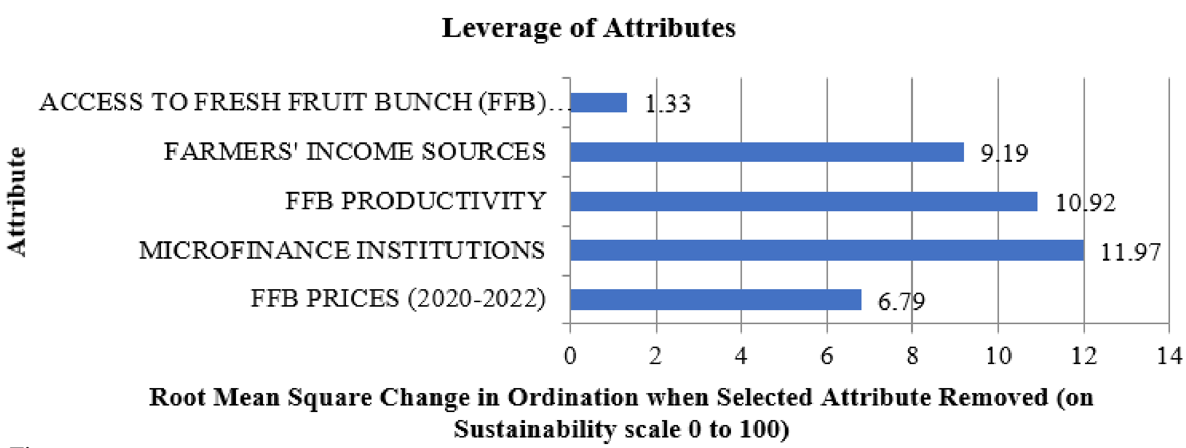

Figure 4.
Leverage analysis of economic dimension.

3.2.1. Sensitive Attributes Affecting the Economic Dimension

Attributes in the economic dimension sensitive to improvements in the sustainability index include microfinance institutions (MFIs) (RMS = 11.97), productivity of fresh fruit bunches (FFB) (RMS = 10.92), and farmers' sources of income (RMS = 9.19). Oil palm farmers in Riau Province still face challenges to access financial institutions to meet business capital needs. This issue is due to the distant locations of financial institutions and the fact that many farmers borrow capital from relatives and lenders. Microfinance institutions in the study area face various problems.

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3.3. Environmental Dimension Sustainability Index and Status

The environmental dimension is an important aspect as it determines the balance between the utilization of natural resources and environmental services. Environmental attributes are selected to reflect how the use of natural resources and the environment impacts sustainability.

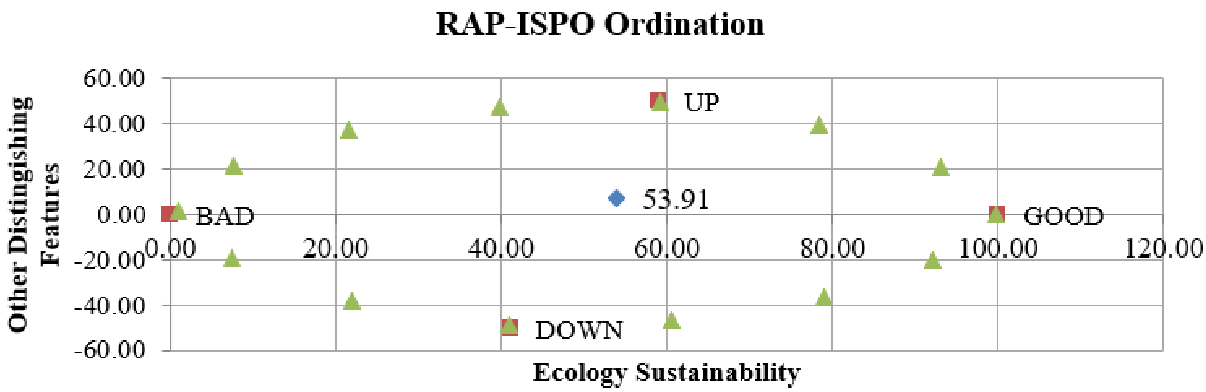

Figure 5.
RAP-ISPO environmental dimension.

Based on the RAP-ISPO analysis results, the environmental dimension index for smallholder oil palm plantations was 53.91%, placing it in the "moderately sustainable" type. This state arises from an absence of understanding and concern among farmers regarding environmental sustainability, which sustains the continuity of the oil palm commodity.

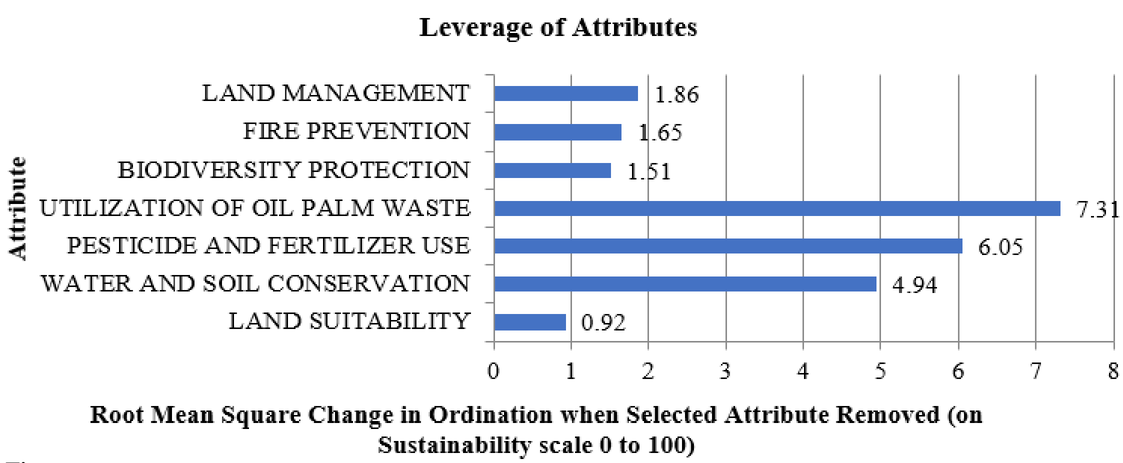

Figure 6.
Leverage analysis environmental dimension.

3.1.1. Sensitive Attributes Affecting the Environmental Dimension

Attributes in the environmental dimension that are sensitive to the sustainability index include oil palm waste utilization (RMS = 7.31), the use of pesticides and inorganic fertilizers (RMS = 6.05), and the conservation of water and soil (RMS = 4.94).

3.4. Technological Dimension Sustainability Index and Status

The technology dimension refers to the utilization and adoption of technology in smallholder oil palm agribusinesses to facilitate oil palm cultivation [11]. Technology is crucial for achieving operational efficiency. When the technology dimension is accessible and supplied, it supports the sustainability of oil palm plantations.

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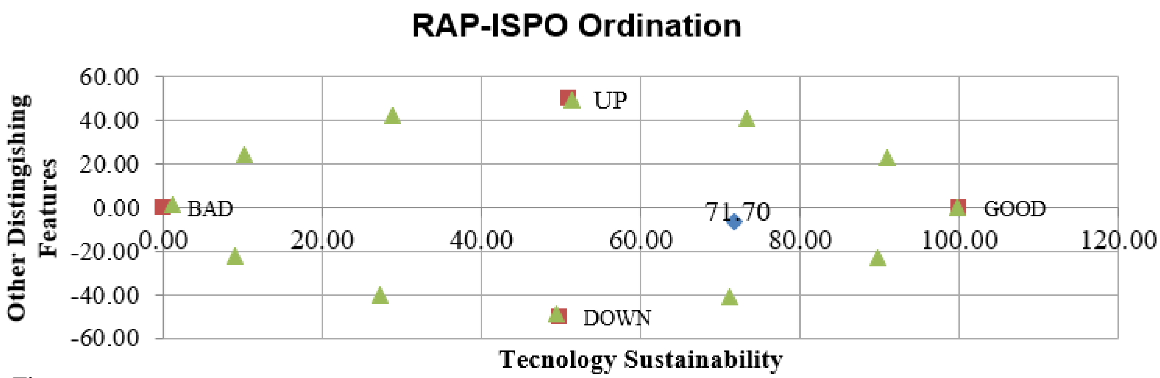

Figure 7.
RAP-ISPO technological dimension.

The RAP-ISPO analysis reveals that the technology dimension index for the sustainability of oil palm plantations was 71.70%, positing it in the "moderately sustainable" category. The relatively high sustainability score for the oil palm industry in the technology dimension in Riau Province is motivated by several variables that received high scores. Industry optimism regarding the prospects of oil palm has generally improved.

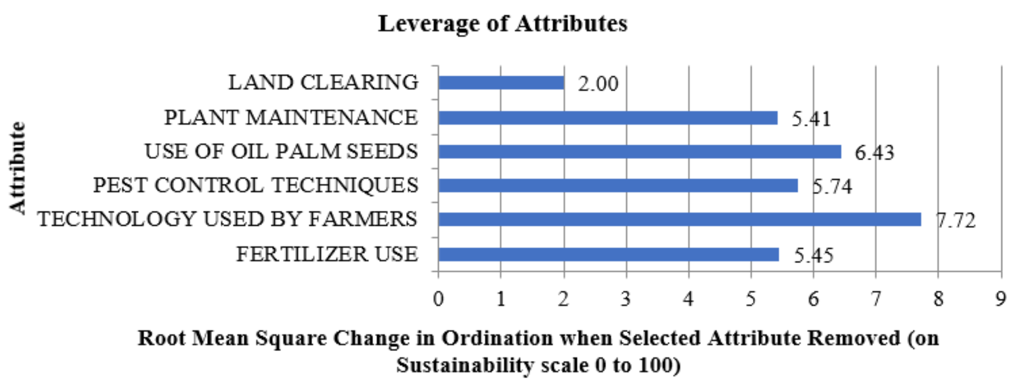

Figure 8.
Leverage analysis of technological dimension.

3.4.1. Sensitive Attributes Affecting Technological Dimension

Attributes in the technology dimension perceptive to improvements in the sustainability index include the technology used by farmers (RMS = 7.72), the use of oil palm seedlings (RMS = 6.43), and pest control techniques (RMS = 5.74).

3.5. Institutional Dimension Sustainability Index and Status

The institutional dimension is a vital component in assessing the sustainability of oil palm plantations. The sustainability of this dimension reflects the ability of groups to integrate and perform institutional functions effectively to facilitate plantation operations [12].

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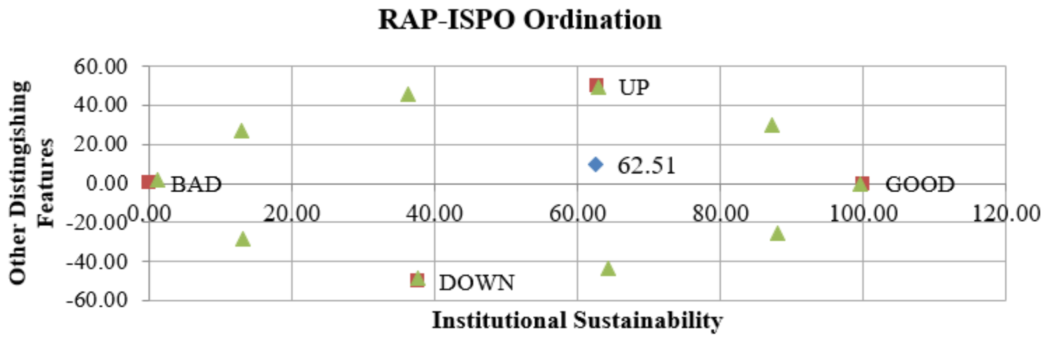

Figure 9.
RAP-ISPO institutional dimension.

The outputs of RAP-ISPO analysis confirm that the sustainability index for the institutional dimension was 62.51%, falling within the range of 51–75, and is considered "moderately sustainable."

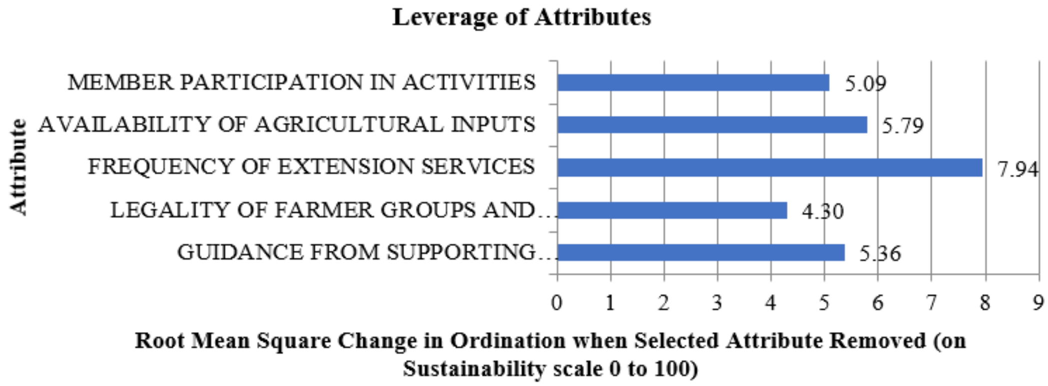

Figure10.
Leverage analysis of institutional dimension.

3.5.1. Sensitive Attributes Affecting Institutional Dimension

Attributes in the institutional dimension that are sensitive to improvements in the sustainability index comprise the frequency of extension services (RMS = 7.94), the availability of agricultural inputs (RMS = 5.79), and the guidance from supporting institutions (RMS = 5.36).

3.6. Accuracy of Analysis

The RAP-ISPO analysis indicates that the goodness of fit is exhibited in the S-Stress value. The S-Stress index is used in MDS analysis to measure the quality of data representation in a multidimensional space. A lower S-Stress value signifies a better data representation in the multidimensional model. The R^2 (coefficient of determination) value is used to assess how well a statistical model (e.g., regression) fits the data. An R^2 value close to 1 specifies that the statistical model completely explicates the data variation. These findings suggest that the MDS estimation model is effective and suitable for measuring sustainability [9]. In a good model, S-Stress should be <0.25 and R^2 should be close to 1 (100%) (see Table 2). The S-Stress and R^2 values demonstrate that all attributes employed and investigated multidimensionally met statistical criteria and were adequate for explaining the sustainability of oil palm plantations in Riau Province.

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Table 2.
Goodness of fit for the sustainability dimension of ISPO and monte Carlo analysis.

Sustainability dimension	S-Stress	R^2	MDS	Monte Carlo	Difference (MDS-MC)
Economic	0.1494	0.9340	60.85	60.14	0.71
Social	0.1481	0.9412	67.54	66.75	0.79
Environmental	0.1452	0.9431	53.91	53.86	0.05
Technological	0.1500	0.9421	71.70	70.73	0.97
Institutional	0.1588	0.9356	62.51	61.57	0.94
Multidimensional scale			63.30		

Table 2. Shows that the S-Stress values ranged from 0.14 to 0.15, and the R^2 values ranged from 0.93 to 0.94, indicating that the goodness of fit in the RAP-ISPO analysis is satisfied. The coefficient of determination (R^2) reflects the extent to which attributes contribute to the sustainability of the analyzed system. If the S-Stress values are met, the configuration of attributes can accurately represent the original data, suggesting that the analyzed indicators are precise and statistically reliable. Monte Carlo analysis is used to estimate the impact of errors in the analysis process with a 95% confidence level. The results in Table 2 signify that the difference between MDS values from the RAP-ISPO and Monte Carlo values was relatively slight, from 0.05% to 0.97%, and did not exceed 5%. These indicate that the error level in attribute assessment is relatively low, the analysis is stable even with repeated iterations, and errors in data input can be minimized. Thus, the confidence level in the sustainability analysis of oil palm plantations is very high.

4. Discussion

4.1. Social Dimension Sustainability

The social dimension is one of the three main indicators of sustainability, focusing on the fulfillment of basic needs in a sustainable manner, including safety, justice, freedom, education, and employment. This study uses six attributes to analyze the social dimension: family member participation, farmer education, occupational health and safety protection, access to healthcare, farmer empowerment, and conflicts between farmers and companies.

The leverage analysis results indicate that sensitive attributes affecting the sustainability of oil palm plantations include occupational health and safety protection, access to healthcare, and farmer education. At the research locations, it was identified that workers often neglected to use personal protective equipment (PPE), leading to continued workplace accidents. For example, inadequate gloves caused hand injuries, not wearing head protection during harvesting led to head injuries, and not using masks during pesticide spraying and fertilization resulted in respiratory problems. Neglecting PPE exacerbated the health and safety conditions of workers. Therefore, this study suggests enhancing access to health and safety training and providing adequate PPE to reduce the risk of accidents and injuries [13].

Several types of hazards pose risks to workers, including biological hazards and chemical hazards. The most common biological hazards in oil palm plantations are insect stings and venomous animal bites. According to key informants, these venomous creatures represent biological hazards, and increasing workers' awareness of the potential dangers posed by these animals can enhance their vigilance in preventing biological risks that threaten health and safety [14]. Chemical hazards present significant risks to the health and safety of oil palm plantation workers. In the palm oil industry, these hazards arise from the use of pesticides and herbicides in the plantations [15].

Owing to the geographical conditions of the oil palm plantations in the study area, which are far from urban centers, accessing healthcare is challenging. The difficulty in accessing medical services often forces farmers to rely on traditional medicines, which can be dangerous and threaten public health, particularly that of the farmers. Oil palm farmers depend on local public health centers and clinics for basic healthcare services. However, the access is often limited due to distance and inadequate facilities. These issues should be a particular concern for the government to provide affordable education and healthcare services to rural communities, especially oil palm farmers in remote villages. With better education, oil palm farmers can enhance their skills, adopt more efficient and sustainable farming

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practices, and improve their overall well-being. Education is a key indicator of human resource development quality, and education level typically impacts technology adoption. Farmer's education level is applied to gage their social conditions, which can indirectly encourage the adoption of sustainability practices [2].

The findings of this study indicate that the sustainability of the oil palm industry in the social dimension is classified under the "moderately sustainable" category. This suggests that some attributes need improvement to achieve full sustainability in oil palm practices. Leverage analysis highlights the attributes that must be taken seriously due to their significant impact on sustainability. The finding is constant with the report of prior research Hariyanti and Syahza [16] which also categorized the social dimension of oil palm plantation sustainability as "moderately sustainable. In other words, it is essential to focus on the key factors to achieve optimal sustainability. By addressing these areas, oil palm plantations can be improved to better align with sustainability principles.

4.2. Economic Dimension Sustainability

In this study, five attributes were to analyze the sustainability of the economic dimension: access to fresh fruit bunch (FFB) marketing, sources of farmer income, farmer productivity, microfinance institutions, and FFB prices (2020-2022). The leverage analysis results indicate that sensitive attributes affecting the sustainability of oil palm plantations in the economic dimension include: microfinance institutions, FFB productivity, and sources of farmer income.

Microfinance institutions (MFIs) in the study area face various issues. Problems with agricultural financing are directly related to complex and bureaucratic credit distribution systems that do not adequately consider the social and cultural conditions of rural areas, making it difficult to address the actual needs of farmers. Three aspects to consider when exploring farmers' access to financing [17] including identifying the various schemes available to oil palm farmers, understanding the perspectives of lenders (both formal and informal) on the effectiveness of diverse financing schemes in meeting farmers' investment needs, such as initial plantation establishment and operational maintenance costs, and identifying the behavior of farmers in borrowing money related to the cash flow of their oil palm plantations. Generally, agricultural ventures are still considered high-risk, with financing remaining limited to production activities and not extending to pre- and post-production activities. Moreover, the development of guarantee institutions and specialized financial institutions for the agricultural sector has not yet progressed [18].

The low productivity of fresh fruit bunches is due to several factors, including the relatively young age of the plants, which are still in the early stages of production, and the aging plants approaching replanting, which leads to decreased productivity. Furthermore, farmers have not optimally applied technology, particularly in orchard maintenance such as fertilization. Plantation management often neglects recommended practices due to limited knowledge and capital, resulting in suboptimal productivity. Efforts to ensure stable oil palm production must be accompanied by improvement of field maintenance through the adoption of good agricultural practices (GAP). By implementing GAP in management, its objectives can be achieved, including improving product quality according to specific standards, ensuring high yields, maintaining healthy production techniques, maximizing efficiency in natural resource use, promoting sustainable agriculture, and reducing environmental risks [19].

Oil palm farmers in Riau Province rely primarily on oil palm cultivation as their foremost source of income, depending solely on fresh fruit bunches (FFB) transactions from plantations due to a lack of skills outside oil palm farming. Only a small portion of smallholder farmers have additional sources of income, such as working as employees, laborers, livestock workers, or traders. This study highlights the importance of the economic dimension as a component of sustainable agriculture. Farmers with additional sources of income tend to have higher earnings compared to those who focus solely on oil palm cultivation [20]. Rural community's income sources can be categorized into on-farm, off-farm, and non-farm sectors [21]. Attention to the welfare of the community, especially farmers, is vital for achieving sustainable agriculture [22].

This study found that the economic dimension of oil palm sustainability fits into the "moderately sustainable" category. While oil palm plantations provide economic benefits, some areas need

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improvement to achieve a higher level of sustainability. Overall, these findings encourage enhancements in the economic dimension to achieve better long-term sustainability and increase benefits for all stakeholders involved.

4.3. Environmental Dimension Sustainability

Environmental issues remain one of the major trials in the growth of the oil palm industry, ranging from deforestation attributable to the expansion of new oil palm plantations to palm oil waste from crude palm oil (CPO) production [23]. This study analyzes the environmental dimension of sustainability using seven attributes: land management, fire prevention, biodiversity protection, utilization of oil palm waste, pesticide and fertilizer use, water and soil conservation, and land suitability. The leverage analysis results indicate that the sensitive attributes affecting the sustainability of oil palm plantations in the environmental dimension are: utilization of oil palm waste, use of pesticides and inorganic fertilizers, and water and soil conservation.

Oil palm waste consists of various types, such as empty fruit bunches, mesocarp fiber, palm shells, and liquid waste from palm oil mills. In the research locations, farmers have not fully utilized palm oil waste due to limitations in extension services, knowledge, infrastructure, and technology for waste management. Most farmers have not processed agricultural waste into fertilizers, animal feed, or pesticides. Oil palm waste contains both organic and inorganic compounds. Organic compounds decompose more easily than inorganic ones and can be broken down by bacteria through aerobic and anaerobic processes. The struggle in decomposing waste impacts environmental sustainability, contributing to pollution load [24].

The use of pesticides and inorganic fertilizers is considered less effective compared to organic alternatives. Excessive and uncontrolled use of pesticides can lead to food contamination and environmental pollution, affecting agriculture and water systems [25]. In oil palm cultivation, fertilizers are crucial. Several factors must be considered when applying fertilizers, including dosage, type, and the content of materials. For instance, even when using high-quality fertilizers, care must be taken to apply them correctly [26]. This study identified that farmers predominantly rely on inorganic pesticides to control pests and inorganic fertilizers to boost productivity. While the level of pesticide use remains within safe limits, it is important to monitor and prevent dependency on chemical pesticides.

Conservation is an effort to protect the environment while considering the benefits that can be obtained in the present. One key objective of soil conservation is to reduce erosion in an area. Soil conservation is important to prevent erosion, repair soil damage, and maintain and enhance land productivity for sustainable use [27]. The research locations feature varied topography, including flatlands, hills, and plantations. The regions are predominantly agricultural but also include fields and settlements. The primary livelihood is farming, including the increasingly popular oil palm plantations. Current issues that farmers face include flooding and waterlogging in peatlands and tidal areas, as well as drought during the dry season. To deal with these challenges, it is essential to conserve soil and water in oil palm cultivation. This involves land management practices integrating soil and water conservation principles into oil palm cultivation (man-made conservation). Technical culture standards for oil palm cultivation, from planting to maintenance, incorporate these conservation principles [28].

The crucial role of soil and water conservation in oil palm plantations must be recognized, especially considering the speedy extension of oil palm farms. Preparing land for new oil palm plantations often involves land clearing, which can lead to soil erosion [29]. The government is expected to provide education on the importance of using organic pesticides and support the development of organic pesticides. For example, oil palm by-products such as empty fruit bunches and palm kernel cake can be processed into livestock feed. The nutritional content of these by-products can enhance feed quality.

This study found the environmental sustainability of oil palm plantations is considered moderately sustainable. The environmental dimension had an index value of 53.91, which is the lowest compared to the social, economic, technological, and institutional dimensions. This value indicates that measures to maintain environmental sustainability are not yet fully effective or evenly implemented across the oil palm industry. Although not in a critical state, there are signs that many environmental challenges

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remain unresolved. The score reflects the need for significant improvements in environmental practices within the oil palm industry, particularly to alleviate negative impacts on ecosystems.

4.4. Technological Dimension Sustainability

The technology dimension involves technology use and adoption to ensure the sustainability of smallholder oil palm plantations and to support the development of oil palm farming [11]. Technology is necessary for achieving operational efficiency in oil palm plantations. When the technological aspect is available and fulfilled, it contributes to the sustainability of oil palm cultivation. A well-managed oil palm plantation should spotlight cultivation technologies that align with good agricultural practice guidelines [30]. In this study, six attributes were used to probe the sustainability of the technology dimension, including land preparation, crop maintenance, use of oil palm seedlings, pest and disease control techniques, technology utilized by farmers, and fertilizer use. The leverage analysis indicates that the sensitive attributes affecting the sustainability of the technology dimension in oil palm plantations are the technology used by farmers, the use of oil palm seedlings, and pest and disease control techniques.

In the oil palm plantations of Riau, technology has not significantly evolved or changed. The technology used by oil palm farmers in the study area remains largely manual. This situation often arises due to various reasons, including limited access to modern technology, high costs associated with advanced equipment, and a lack of knowledge or training in using new technologies. Some common manual technologies used by oil palm farmers include manual harvesting, field maintenance, fertilization, and fresh fruit bunch transportation. In manual harvesting, fresh fruit bunches are often taken using a sickle or machete attached to a long pole. Workers cut the bunches from the trees and gather them manually. In field maintenance, tasks such as pruning leaves and weed control are frequently performed using simple tools like machetes, hoes, and sickles. Fertilizer application is usually done manually, with farmers spreading fertilizer around the base of the trees. Transporting the harvested fresh fruit bunches to collection points is often carried out using hand carts.

In agricultural innovation, the use of superior seeds is fundamental. These seeds directly impact the production potential per hectare, ensuring successful palm oil cultivation [31]. However, many farmers in the study area still use non-certified seeds, especially for older plants. They often choose uncertified seeds due to the high cost of certified seeds [6]. In Indonesia, superior seeds are the results of crossing *Dura* (female parent) and *Pisifera* (male parent). The crossbred results, known as *Tenera*, are still widely used in oil palm plantations [32]. Additionally, the adoption of pest control technologies is still limited among farmers, resulting in low knowledge and interest in pest management.

This study disclosed that the sustainability of oil palm cultivation within the technology dimension is categorized as "moderately sustainable," with an index value of 71.70. This is the highest value among the social, economic, environmental, and institutional dimensions. This indicates that, compared to other dimensions, the application of technology in oil palm plantations in Riau Province is more advanced and better supports sustainability. To maintain and enhance this sustainability, it is crucial to pay serious attention to this variable to ensure that innovations and technology can sustainably improve the productivity of the CPO industry.

4.5. Institutional Dimension Sustainability

The institutional dimension is crucial for ensuring the efficiency of oil palm cultivation and requires the role of institutions to facilitate access to assistance. This study identifies five attributes used to analyze the sustainability of the institutional dimension: farmer participation in farmer groups/cooperatives, availability of agricultural inputs, frequency of extension services, legal status of farmer groups/cooperatives, and guidance from supporting institutions. The leverage analysis results indicate that the sensitive attributes impacting the sustainability of oil palm plantations in the institutional dimension are the frequency of extension services, availability of agricultural inputs, and guidance from supporting institutions.

In Riau Province, extension activities in the plantation sector have not received adequate attention from the government [20]. In the study areas, extension services were conducted approximately every

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six months. This indicates that the government's and extension agencies' focus on improving human resources in this region remains very low. Several studies have concluded that more extension efforts are needed for farmers to fully comply with ISPO certification standards [33-35]. Training can positively impact the environment by increasing knowledge about agricultural chemicals, integrated pest management, and promoting areas designated for conservation [36-38]. Production facilities are crucial for overseeing oil palm plantations. Essential production facilities include certified oil palm seeds, fertilizers, and chemicals such as pest and disease control products. Farmers report that production facilities, especially certified oil palm seeds, are not easily accessible. Even when available, their prices are relatively high. The difficulty in obtaining seeds, fertilizers, and chemicals is a significant concern for farmers. This study finds that the sustainability of oil palm in the institutional dimension is moderately sustainable, with an index value of 62.51.

5. Conclusion

The analysis results indicate that the sustainability of oil palm plantations is moderate, with the highest index value in the technology dimension at 71.70% and the lowest in the environmental dimension at 53.91%. To achieve higher sustainability, it is significant to mitigate the environmental impacts while continuing to support and expand technology implementation. Moreover, strengthening institutional dimensions and improving social and economic well-being will further ensure that oil palm plantation practices can positively contribute to sustainable development. In summary, sustainable oil palm cultivation involves a wide-ranging approach that balances economic, social, environmental, technological, and institutional considerations. Addressing these challenges entails cooperation between the government, industry, and communities. Adopting sustainable practices not only benefits the environment and local communities but also provides long-term advantages and enhances the reputation of the oil palm industry. Given the complexity of sustainability in the oil palm sector, future approaches to assessing sustainability could benefit from broader perspectives, such as landscape-level and jurisdictional analyses, to transform agricultural practices.

Author Contributions:

Siti Hartinah was responsible for conceptualizing the idea, collecting data, literature review, analyzing the data, and writing the manuscript. Meanwhile, Dwidjono Hadi Darmanto, Any Suryantiny, Arini Wahyu Utami were in charge of conceptualizing the vision, guidance, and supervision of datacollection and analysis, reviewing,and revising the manuscript.

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Data Availability:

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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