International Journal of Advanced and Applied Sciences, 13(1) 2026, Pages: 162-173

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: https://www.science-gate.com/IJAAS.html

Strategies for enhancing the implementation of combine harvesters in rice harvesting in Indramayu Regency, Indonesia

Momon Rusmono [1, *], Intan Kusuma Wardani [2], Alya Husnul Khotimah [3], Erniati Erniati [2]

[1]*Sustainable Agricultural Extension Study Program, Agricultural Development Polytechnic Bogor, Bogor, Indonesia*
[2]*Agricultural Mechanization Technology Study Program, Agricultural Development Polytechnic Bogor, Bogor, Indonesia*
[3]*Agricultural Extension Study Program, Jenderal Soedirman University, Purwokerto, Indonesia*

ARTICLE INFO

Article history:
Received 6 August 2025
Received in revised form
18 December 2025
Accepted 7 January 2026

Keywords:
Combine harvester performance
Rice harvesting efficiency
Postharvest losses
Farmer effectiveness
Agricultural mechanization

ABSTRACT

The use of combine harvesters is important for replacing manual labor, speeding up the harvesting process, reducing postharvest losses, and lowering operational costs, thereby improving the effectiveness and efficiency of rice harvesting. This study aimed to evaluate the performance and conformity of combine harvesters under different field conditions and to develop strategies to increase their use in rice harvesting. The research was conducted from April to June 2025 in the Lelea, Kroya, and Cikedung subdistricts of Indramayu Regency, Indonesia. Performance tests were carried out on rice fields that were ready for harvest, and data were collected from 120 farmer respondents. A quantitative research approach was used, with data analyzed using descriptive statistics and Partial Least Squares Structural Equation Modelling (PLS-SEM). The results showed that the combine harvester specifications conformed to Indonesian National Standard 8185:2019 by 91.67%. The operational efficiency of the combine harvesters was 63.57% in medium-depth fields and 68.11% in shallow fields. The average postharvest loss was 2.08 kg, including a header loss of 0.009% and a threshing loss of 0.001%. The PLS-SEM results indicated that government support, land and crop characteristics, and agricultural institutional support were the most significant factors influencing farmers' effectiveness in using combine harvesters, together explaining 70.60% of the variance. Based on these findings, strategies were proposed to improve the utilization of combine harvesters by strengthening farmers' effectiveness in Indramayu Regency.

1. Introduction

The agricultural sector plays a strategic role in achieving food security and improving the Indonesian economy. Rice farming significantly contributes to the development of the socio-economic structure of rural communities. This situation explains the relationship between aspects of rural life and government policies, agricultural mechanization, infrastructure development, and increased access to agricultural knowledge and information (Hossain et al., 2015). Indramayu Regency is the largest rice production center in West Java Province. In 2024, the total rice paddy area reached 212,866 hectares, with a production of approximately 1,399,352 tons of dry milled grain. Indramayu Regency is projected to significantly contribute to national food self-sufficiency. However, rice farming faces challenges, such as labor constraints, limited agricultural tools and machinery, and a lack of farmer knowledge and competence regarding post-harvest handling. This often results in inefficient harvest times and high yield losses. A comprehensive rice farming optimization strategy is needed to increase rice productivity, stimulate economic growth, and support food self-sufficiency (Hossain et al., 2015).

Postharvest rice handling includes harvesting, threshing, drying, and storing the grain. There are two methods used in the rice harvesting process: conventional and modern. Conventional harvesting using sickles, *ani-ani*, or *gebotan* (traditional harvesting tools) can increase harvest losses. Furthermore, inappropriate harvesting systems, such as temporary stacking of paddy fields, gathering rice at the threshing area, and delaying threshing,

* Corresponding Author.
Email Address: monroes2405@gmail.com (M. Rusmono)
https://doi.org/10.21833/ijaas.2026.01.017
Corresponding author's ORCID profile:
https://orcid.org/0009-0003-9420-7925

result in postharvest losses of up to 12.7%, while the use of combine harvesters results in lower losses of 4.61%. Furthermore, conventional harvesting requires 40% more labor than using a combine harvester (Hossain et al., 2015; Wang et al., 2021). Postharvest rice losses are primarily caused by farmers' limited capacity to implement good postharvest systems, as well as rudimentary postharvest management systems (Myeni et al., 2019). Postharvest losses are also influenced by the timing of harvest, as harvesting overripe rice can potentially increase grain shattering (Hossain et al., 2015). It is shown that a pre-harvest loss of 1.08% and a threshing loss of 0.18% when using a combine harvester. This indicates that the use of a combine harvester can reduce yield losses and increase harvesting efficiency. This efficiency includes aspects of time, labor, and operational costs, making it a superior alternative to manual harvesting methods (Harel et al., 2022; Sarkar et al., 2025). The use of a combine harvester has been proven to overcome problems related to labor shortages, speed up the harvest process, and minimize crop losses (Li and Xu, 2022; Liu et al., 2023; Tang et al., 2017).

Combine harvesters are used to cut, distribute, separate, and clean rice grains (Hossain et al., 2015; Wang et al., 2021). The use of combine harvesters has been proven to save harvest time, reduce yield losses, and reduce operational costs, thereby increasing rice harvesting efficiency. From a technical perspective, combine harvester performance testing aims to ensure optimal machine operation, minimizing yield losses due to the interaction of several factors, including operator competence, plant characteristics, land conditions, machine specifications, and harvesting machine maintenance and operation (Hossain et al., 2015; Wang et al., 2021). Land conditions have been shown to affect fuel consumption. If the land is muddy, the wheels can slip, reducing the speed and ease of operation of the machine, thus increasing fuel consumption. Combine harvester performance tests show a theoretical field capacity of 0.36 ha/hour, an effective field capacity of 0.18 ha/hour, and an efficiency of 63.21%. According to Desrial et al. (2024), harvesting costs decrease from IDR 3,531,577/ha for manual harvesting to IDR 1,857,143/ha using a combine harvester. The introduction of harvesting tools in the form of combine harvesters is starting to be promoted as a solution to optimize rice farming because it can increase harvest efficiency and productivity (Fu et al., 2022).

From a social perspective, the success of implementing combine harvester technology in rice farming is determined by the level of farmer adoption. The level of farmer adoption of combine harvesters is influenced by the suitability, complexity, and profitability of the innovation. Furthermore, farmer readiness and adoption are strongly influenced by the availability of support systems, including land conditions, infrastructure, farmer institutions, labor availability, and government policy support (Wang et al., 2021). Research in Malaysia indicates that factors that can influence farmer satisfaction with using combine harvesters include the quality and quantity of harvests, operational staff services, worker skills, and operator costs. In addition, research by Blas et al. (2022) in the Philippines showed that many farmers accept combine harvesters because they are proven to be more effective in harvesting rice than manual methods. Combine harvesters can reduce harvesting costs, increase farmer income, save costs, and increase productivity. They are also supported by the government as an alternative rice harvesting method. Malanon dan Pabuayon (2022) showed that combine harvesters in the Philippines are more widely adopted by farmers with higher education, higher incomes, larger land holdings, and irrigated lowland areas. Research by Esgici et al. (2016) in Turkey showed that the relationship between combine harvester age and rice yield is not influenced by other factors such as land suitability, operator skills, and machine maintenance.

The use of combine harvesters in Indonesia is increasing due to the need for harvesting efficiency and the labor crisis during harvest time. In several locations in Indonesia, high adoption rates are influenced by access to information and interaction within farmer groups, low yield losses, and high harvest speeds (Arsyad et al., 2025; Desrial et al., 2024). Adoption challenges remain in developing countries due to economic constraints, infrastructure limitations, and market barriers (Daum and Birner, 2020; Diao et al., 2020), although increased mechanization has been shown to improve harvest yields and labor efficiency (Gebiso et al., 2024; Olasehinde-Williams et al., 2020).

Farmers in Indramayu Regency have adopted combine harvesters, but their use has not been effective. Effective use of combine harvesters requires the availability and easy access of adequate combine harvesters, suitable land and crop characteristics, and government policy support (Malanon and Pabuayon, 2022; Wang et al., 2021). Furthermore, the effective use of combine harvesters also requires the support of agricultural institutions, such as farmer institutions, agricultural extension services, and mechanization services. Efforts to increase combine harvester use while supporting farmer effectiveness require a comprehensive, systematic, and contextual implementation model and strategy. This aims to mitigate potential problems such as wetland damage, reduced labor demand, and inequality in access to technology. Farmer effectiveness in using combine harvesters depends not only on the machine's technical performance but also on the alignment of the surrounding social system to facilitate this transformation. Farmer effectiveness is influenced by benefits, target achievement, and sustainability (Wang et al., 2021). Therefore, optimization strategies addressing both social and technical aspects are needed to increase combine harvester use. Based on this background, this study aims to verify and evaluate the performance of combine harvesters under varying land conditions. In addition, the study seeks to formulate strategies to enhance the utilization of combine harvesters, supported by farmers' effectiveness in rice harvesting in Indramayu Regency. This research is not only intended to develop practical, locally appropriate implementation strategies but also aims to contribute to the formulation of agricultural development policies and the strengthening of agricultural institutions.

2. Research method

The research was conducted from April to June 2025 in Lelea, Kroya, and Cikedung Sub-districts, Indramayu Regency. The sites selected for evaluating combine harvester performance were rice fields ready for harvest. A total of 120 farmers participated as respondents in this study. Data were collected through measurements, performance tests, questionnaires, in-depth interviews, and direct field observations. This research employed a quantitative approach with a causal (cause–and–effect) research design. Data were analyzed using descriptive methods and Partial Least Squares Structural Equation Modelling (PLS-SEM). The study parameters encompassed both technical and social aspects. The tools and materials used included a combine harvester, measuring tape, stopwatch, stakes, sacks, scales, and questionnaires.

2.1. Technical aspects

2.1.1. Combine harvester performance test and postharvest losses

The performance test parameters of the combine harvester included the measurement of theoretical field capacity (TFC), effective field capacity (EFC), work efficiency (η), and harvest losses (Wang et al., 2021). The combine harvester operated following the harvesting pattern in the field, with a working area of 10 × 2 m^2, and data collection was repeated three times. These performance test parameters were calculated using the following equations:

a. Theoretical field capacity (TFC)

$$TFC = Wt \times vt \times 0.36$$

where, TFC is the theoretical field capacity (ha/h), *Wt* is the theoretical working width (m), *vt* is the forward speed without load (m/s), and 0.36 is the unit conversion factor.

b. Effective Field Capacity (EFC)

$$EFC = \frac{A}{t}$$

where, EFC is the effective field capacity (ha/h), *A* is the actual harvested area (ha), and *t* is the effective operating time (h).

c. Work Efficiency (η)

$$\eta = \frac{EFC}{TFC} \times 100\%$$

where, η is the field efficiency (%), EFC is the effective field capacity (ha/h), and TFC is the theoretical field capacity (ha/h).

d. Harvest Losses

Header loss was calculated by collecting and weighing the panicles and grains that were not harvested after the combine harvester passed through the field.

$$\text{Header loss} = \frac{S1}{Xtotal} x100\%$$

where, S_1 is the weight of unharvested and scattered rice in the plot (g), and *Xtotal* is the total threshed grain yield plus all losses in the test plot.

Threshing loss was calculated by collecting and weighing the panicles and grains at several stages, including cutting, threshing, separation, and cleaning.

$$\text{Threshing loss} = \frac{S2}{Xtotal} x100\%$$

where, S_2 is the weight of rice remaining inside the machine (g), and *Xtotal* is the total threshed grain yield plus all losses in the test plot (g).

2.1.2. Verification test of the combine harvester

The verification test aimed to measure the accuracy of the specifications of agricultural machinery, in accordance with the parameters of the Indonesian National Standard (INS) (Regulation of the Minister of Agriculture No. 7 of 2007). The dimensional and material testing parameters were adjusted to INS 8185:2019 concerning Rice Combine Harvester, Quality Requirements and Test Methods, which include machine type, maximum engine power, overall dimensions, operational weight, cutting height range from the ground, engine shaft rotation during harvesting, actual cutting width, effective field capacity, harvesting road speed, maximum fuel consumption, percentage of grain losses, and grain cleanliness level.

2.2. Social aspect

2.2.1. Research data and structural model

It was hypothesized that government support (X_1), the availability and accessibility of combine harvesters (X_2), land and crop characteristics (X_3), and agricultural institutional support (X_4) would significantly influence farmer effectiveness in the utilization of combine harvesters (Y). The indicators of the government support variable (X1) comprised program support (X_{11}), regulatory support (X_{12}), and facilitation support (X_{13}). The indicators of the availability and accessibility of combine harvesters' variable (X_2) included the availability of combine harvesters (X_{21}), accessibility to combine harvesters (X_{22}), and the availability of other postharvest equipment (X_{23}). The land and crop characteristics variable (X_3) was measured through land conditions (X_{31}), farm road conditions (X_{32}), and crop conditions (X_{33}). The agricultural institutional support variable (X_4) encompassed farmer organizations (X_{41}), agricultural extension services (X_{42}), and mechanization services (X_{43}). Farmers' effectiveness in the use of combine harvesters (Y) was assessed based on perceived usefulness (Y_1), goal attainment (Y_2), and sustainability (Y_3) (Wang et al., 2021). The structural model of the study, which illustrates the causal relationships among the latent variables, is presented in Fig. 1.

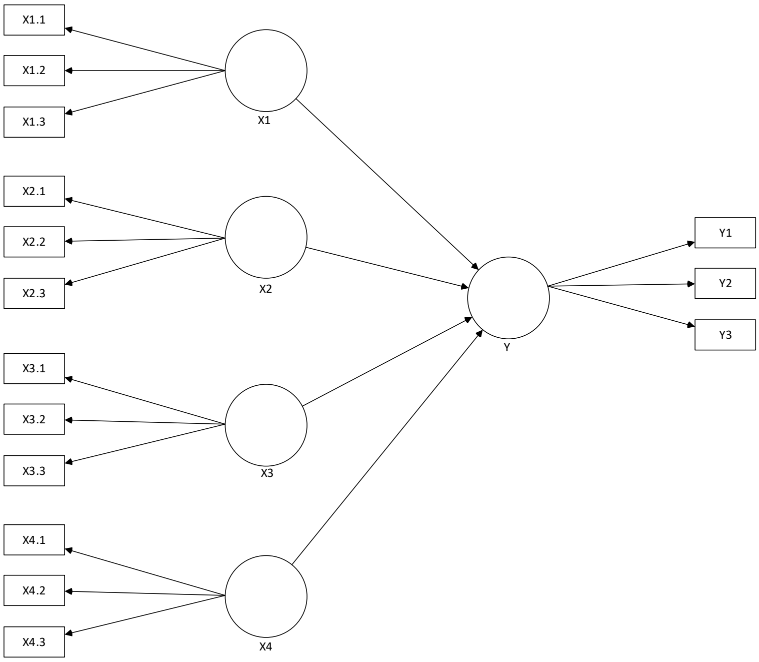

Fig. 1: Research structural model

2.2.2. Measurement model analysis

In this study, Partial Least Squares Structural Equation Modelling (PLS-SEM) was employed to determine the indicators that met the criteria for convergent validity. According to Hair et al. (2014), an indicator is considered to have adequate convergent validity if the outer loading value is ≥ 0.708 and the Average Variance Extracted (AVE) is ≥ 0.50. Subsequently, for the indicators that satisfied the criteria of convergent validity, bootstrapping analysis was conducted to identify the significance of the relationships among variables.

3. Results

3.1. Combine harvester performance test

The performance test of the combine harvester aimed to assess its feasibility, reliability, and operational safety in the field. Performance evaluation was based on three parameters: theoretical field capacity (TFC), effective field capacity (EFC), and field efficiency. These parameters were used to determine the operational capability of the machine under different field conditions. The results indicate that combine harvester performance was influenced by land characteristics, which directly affected the ease of operation during harvesting. In this study, two types of rice field conditions were identified: medium mud and shallow mud. The performance results for each condition are summarized in Table 1.

Based on Table 1, the field efficiency of the combine harvester in medium-mud fields was 63.57%, whereas in shallow-mud fields it reached 68.11%. These results are consistent with similar studies reporting a combine harvester efficiency of 63.59%.

The lower efficiency observed in medium-mud fields can be attributed to the soil characteristics, where the mud depth ranged from approximately 10–30 cm. This finding is in line with Wang et al. (2021), who stated that land conditions, including texture, moisture content, bulk density, and bearing capacity, significantly affect combine harvester efficiency during harvesting operations.

Table 1: Performance test of the combine harvester under different field conditions

Field code	Field condition	TFC (ha/h)	EFC (ha/h)	Efficiency (%)
1	Medium field	0.31	0.19	63.57
2	Shallow field	0.57	0.38	68.11

Soils with high moisture content tend to increase wheel slip, thereby elevating energy consumption. In addition, soils with low bearing capacity may cause the machine to sink and become unstable. Furthermore, Hossain et al. (2015) reported that uneven fields make combine harvester operation more difficult due to mud accumulation on the wheels. In the present study, land conditions were shown to affect operational ease and, consequently, the harvesting efficiency of the combine harvester. Efficiency was higher in shallow-mud fields compared with medium-mud fields. Therefore, land conditions are proven to influence operational performance and are closely correlated with the level of harvest losses.

3.2. Harvest loss test

Harvest losses in the use of combine harvesters occurred during the cutting, threshing, and packaging stages (Wang et al., 2021). According to Wang et al. (2021), harvest losses are caused by the interaction of various factors, particularly land conditions, especially in medium-mud rice fields. Deep muddy fields make it difficult to operate the combine harvester effectively. It is evident that operating combine harvesters on muddy and uneven land causes the wheels to slip, reducing operational smoothness. Such conditions ultimately lead to higher harvest losses. Therefore, in this study, harvest loss analysis and testing were carried out, and the results are presented in Table 2.

Based on Table 2, the yield loss was 2.08 kg, while the average header loss of the combine harvester was 0.009%, and the average threshing loss was 0.001%. These findings are supported by the total loss test of the combine harvester, which was recorded at 0.065% (Desrial et al., 2024). This value is considerably lower than the harvest loss reported in other studies using combine harvesters, ranging between 2.85% and 4.9%. Therefore, it can be concluded that the combine harvester meets the requirements of the Indonesian National Standard 8185:2019 on Multi-Commodity Harvesting Machines, which specifies that the total paddy loss should be less than 2%.

Harvest losses are influenced by several factors, including operator skill, operating speed, and reel height. In the present study, the operator demonstrated a high level of skill with extensive working hours, which contributed to minimizing harvest losses. Furthermore, the good condition of the combine harvester contributed to minimizing both header loss and threshing loss. Zhu et al. (2020) emphasized that cylinder speed and the concave clearance have a significant influence on grain breakage and losses due to separation with chaff. Similarly, Lashgari et al. (2008) reported that higher cylinder speeds and narrower concave clearances increased wheat grain breakage, with optimal performance achieved at a cylinder speed of 900 rpm, a forward speed of 1.8 km/h, and a concave clearance of 25 mm. In addition, Amrullah and Pullaila (2019) found that operator skills also play a critical role in reducing harvest losses. Although the use of combine harvesters can lower harvest losses to an average of 3.52%, this reduction is only optimal when operators have received prior technical training or extension services. Esgici et al. (2016) further highlighted that harvest losses are influenced not only by the machine's age but also by other factors, particularly operator ability and skill. In line with these findings, it was reported that the Combine Model 2002 was able to produce lower harvest losses compared to newer models.

Table 2: Analysis of harvest losses in combine harvester operation

Location	Gross weight (kg)	Net weight (kg)	Yield loss (kg)	Header loss (%)	Threshing loss (%)
1	97.90	95.20	2.70	0.000	0.004
2	39.00	38.30	0.70	0.015	0.000
3	42.00	41.70	0.30	0.006	0.000
4	51.50	50.50	1.00	0.018	0.001
5	51.70	50.80	0.90	0.015	0.002
6	153.00	146.10	6.90	0.000	0.001
Mean	72.52	70.43	2.08	0.009	0.001

Yield loss = Gross weight – Net weight

Appropriate adjustments of the harvesting equipment, combined with the operator's expertise in regulating forward speed, header settings, and machine maintenance, are crucial in minimizing harvest losses. Abdalla et al. (2021) demonstrated that increasing forward speed significantly increased header losses, with the total loss at 6 km/h reaching 90.09 kg/ha, much higher than 31.75 kg/ha at 4 km/h. The main cause of this loss was the increased vibration of the header unit and the mismatch between forward speed and reel speed, which caused grains to detach from the panicle before processing. Taken together, these studies confirm that operator reliability is essential when managing varying field conditions. Therefore, strengthening the technical capacity and knowledge of both operators and landowners is critical in determining the optimal harvest timing to achieve efficient combine harvester operation.

3.3. Combine harvester verification test

The verification test of the combine harvester was conducted to confirm the conformity between the technical specifications stated in INS 8185:2019 and the actual machine conditions. A summary of the verification test results is presented in Table 3. Based on Table 3, only one parameter, which is fuel consumption, was found to be noncompliant among the twelve observed parameters. Therefore, it can be concluded that the conformity of the combine harvester specifications with INS 8185:2019 is 91.67%. Field conditions affect fuel consumption because operations on deep, muddy fields require longer working times and heavier loads. It is also reported that muddy soil can cause wheel slippage, increasing machine workload and fuel consumption. In this study, the combine harvester performance tests were conducted on two field conditions: Shallow muddy and deep muddy rice fields. As a result, fuel consumption during the tests exceeded the INS standard, measuring higher than 7.5 L/h.

Table 3: Verification test of the combine harvester

Parameters	Unit	Combine harvester	INS	Conformity
Maximum engine power	kW	75	60-80	Conformed
Length	mm	5155	4600 – 5400	Conformed
Width	mm	2530	2100-3100	Conformed
Operating weight	kg	3380	2300-3500	Conformed
Cutting height ranges from the ground	cm	45	70-900	Conformed
Motor shaft rotation when harvesting	rpm	2600	2000-3000	Conformed
Actual cutting width	mm	1940	1600-2000	Conformed
Effective field capacity	ha/hour	0.57	0.45	Conformed
Harvesting road speed	km/hour	2.02	3-6	Conformed
Maximum fuel consumption	l/hour	35	10	Not conformed
Grain loss percentage	%	0	3.5	Conformed
Grain cleanliness	%	± 97.11	90	Conformed

Verification of combine harvesters against INS 8185:2019 is essential to ensure that the specifications provided by manufacturers conform to national standards, thereby guaranteeing capacity, quality, efficiency, and operational safety. It is stated that these standards serve as the basis for selecting the appropriate class of combine harvester according to field topography and farm accessibility. The results of the verification tests were largely in accordance with INS 8185:2019. This is supported by the study of Desrial et al. (2024), which reported an effective field capacity of 0.504 ha/h and a postharvest loss percentage of 0.067%. Grain cleanliness reached 97.69% while the harvesting speed was 3.70 km/h, the actual cutting width was 1.8 m, and engine speed 2,500 rpm. Similarly, Ahmad and Khadzir (2024) reported an effective field capacity of 0.94 ha/h with a postharvest loss of 2.3%. All these values comply with the applicable INS standards.

The alignment between the technical specifications of combine harvesters and farmers' preferences significantly influences purchasing and utilization decisions. According to Wang et al. (2021), the header design of a combine harvester affects yield losses, which is closely related to the actual cutting width. Increasing the availability of combine harvesters in a region can enhance adoption rates among farmers. Government-provided combine harvesters also facilitate farmer access to mechanized harvesting. Saputra (2021) highlighted that capacity, per-hectare production, quality, and harvesting costs influence farmers' decisions when selecting a combine harvester. Verification data can therefore serve as a reference for farmers to choose combine harvesters that meet their specific needs.

3.4. Social aspect

Based on the verification test results, the conformity of the combine harvester with INS 8185:2019 was 91.67%, while the percentage of grain loss was below 3.50%. This indicates that the use of the combine harvester in this study is considered effective and reliable in supporting rice farming operations. The effectiveness of combine harvester utilization in Indonesia is influenced by the interaction of several factors, including socio-economic aspects, biophysical and environmental conditions, regulations, and technology. Therefore, efforts are needed to enhance the comprehensive use of combine harvesters to support the sustainable optimization of farming practices (Winarno et al., 2025). In this study, the measurement and analysis of combine harvester utilization were assessed through variables such as government support, availability and accessibility of combine harvesters, land and crop characteristics, agricultural institutional support, and farmer effectiveness.

3.4.1. Description of research variables

Descriptive statistics were employed to systematically summarize the data and explain the characteristics of the research variables. The results of the descriptive analysis are presented in Table 4.

The relatively high proportion of respondents who rated government support in the low (41.67%) and medium (45.80%) categories indicates persisting limitations in terms of programmatic, regulatory, and facilitative support from both the Ministry of Agriculture and the Indramayu District Agricultural Office for the development and utilization of combine harvesters. The availability and accessibility of combine harvesters were assessed as being in the medium category (59.77%). This suggests that although the technology has become accessible to farmers, its utilization remains suboptimal. This condition is likely attributable to the limited number of available units, uneven distribution, and insufficient technical skills among farmers and operators (Akter et al., 2024). Land and crop characteristics were also categorized as medium (55.77%). This indicates that agroecological factors such as land conditions, farm road infrastructure, and crop characteristics are not yet fully aligned with the effective use of combine harvesters. Similarly, agricultural institutional support was perceived by farmers as being in the medium category (53.63%). This finding reflects that the presence and role of farmers' organizations, agricultural extension services, and mechanization services are not yet fully functioning in supporting farmers' effectiveness in using combine harvesters. Strengthening the role of these institutions in a more integrated manner would foster improvements in farmer effectiveness in utilizing combine harvesters.

Farmer effectiveness refers to the ability of farmers to optimally manage resources in order to achieve maximum agricultural outcomes. In this study, farmer effectiveness in using combine harvesters was also categorized as medium (51.10%). This indicates that farmers' effectiveness, encompassing the perceived usefulness of technology, goal attainment, and the sustainability of rice farming, still requires improvement.

3.4.2. Outer model evaluation

In this study, the outer loading analysis was conducted to assess the validity of the measured constructs, while the Average Variance Extracted (AVE) was used to evaluate convergent validity. Multicollinearity analysis was carried out to examine the extent to which each indicator within a construct is highly correlated with other indicators in the model.

One of the approaches employed was the calculation of the Variance Inflation Factor (VIF). A high VIF value indicates excessive correlation among indicators, which may compromise the stability of coefficient estimation in the PLS-SEM model. The results of the reliability and convergent validity tests are presented in Table 5.

Table 4: Descriptive statistics of research variables

Indicator	Percentage (%)			Total
	Low	Moderate	High	
Government support (X_1)				
Program support (X_{11})	40.00	43.30	16.70	100.00
Regulatory support (X_{12})	37.50	53.30	9.20	100.00
Facility support (X_{13})	47.50	40.80	11.70	100.00
Mean	41.67	45.80	12.53	100.00
Availability and accessibility of the combine harvester (X_2)				
Availability of the combine harvester (X_{21})	15.80	63.40	20.80	100.00
Accessibility of the combine harvester (X_{22})	8.30	69.20	22.50	100.00
Availability of other post-harvest equipment (X_{23})	3.30	46.70	50.00	100.00
Mean	9.13	59.77	31.10	100.00
Land and crop characteristics (X_3)				
Land condition (X_{31})	7.50	65.00	27.50	100.00
Farm road condition (X_{32})	1.80	61.70	27.50	100.00
Crop condition (X_{33})	5.00	59.20	35.80	100.00
Mean	6.99	55.77	27.24	100.00
Agricultural institutional support (X_4)				
Farmer organizations (X_{41})	19.20	57.50	23.30	100.00
Agricultural extension services (X_{42})	10.00	54.20	35.80	100.00
Mechanization services (X_{43})	23.30	49.20	27.50	100.00
Mean	17.50	53.63	28.87	100.00
Farmer effectiveness (Y)				
Perceived usefulness	1.70	47.50	50.80	100.00
Goal attainment	1.70	53.30	45.00	100.00
Sustainability	3.30	52.50	44.20	100.00
Mean	2.23	51.10	46.67	100.00

Table 5: Results of reliability and convergent validity tests

Variable	Indicator	AVE	Loading factor	VIF
Government support	Program support (X_{11})	0.857	0.927	3.40
	Regulatory support (X_{12})		0.956	3.94
	Facility support (X_{13})		0.894	2.92
Availability and accessibility of the combine harvester	Availability of the combine harvester (X_{21})	0.908	0.936	11.03
	Accessibility of the combine harvester (X_{22})		0.928	12.10
	Availability of other post-harvest equipment (X_{23})		0.993	33.51
Land and crop characteristics	Land condition (X_{31})	0.816	0.881	2.43
	Farm road condition (X_{32})		0.915	2.60
	Crop condition (X_{33})		0.913	2.69
Agricultural institutional support	Farmer organizations (X_{41})	0.762	0.845	2.46
	Agricultural extension services (X_{42})		0.871	1.74
	Mechanization services (X_{43})		0.902	3.09
Farmer effectiveness	Perceived usefulness	0.706	0.904	2.65
	Goal attainment		0.883	2.45
	Sustainability		0.720	1.30

Based on Table 5, the Average Variance Extracted (AVE) values for all indicators were ≥0.50, indicating that the measurement model is both reliable and valid. The loading factor values for all indicators exceeded the threshold of 0.708. Furthermore, the results of the Variance Inflation Factor (VIF) analysis suggest that the model is generally free from multicollinearity issues (VIF≤5), with the exception of the construct related to the availability and accessibility of combine harvesters. Accordingly, the measurement model can be considered adequate, and the analysis may proceed to the evaluation of the structural model.

3.4.3. Inner model evaluation

Hypothesis testing aims to examine the relationships between the independent and dependent variables, as indicated by the path coefficient values. The structural model analysis is presented in Fig. 2, while a summary of the model fit evaluation is provided in Table 6.

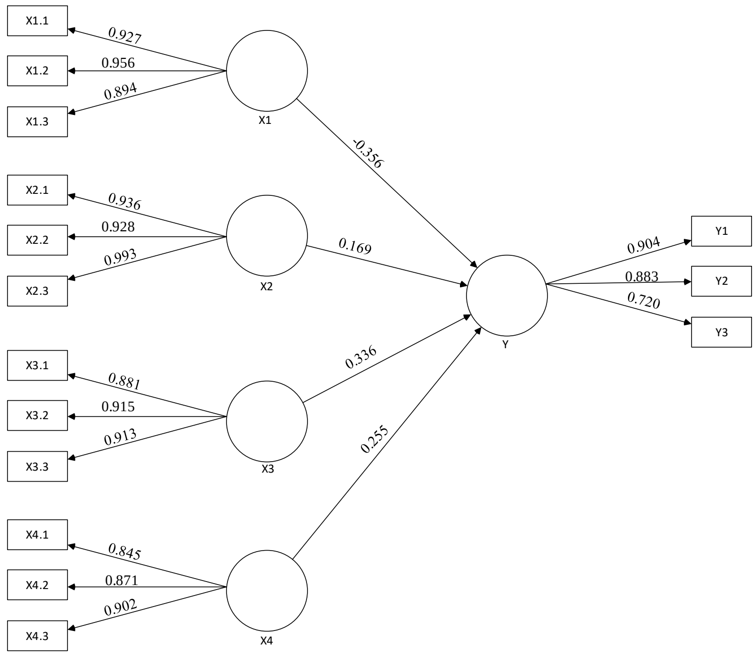

Fig. 2: Structural model results

Table 6: Model fit test results

Variable	Path coefficient	T-statistics	P-values	R^2	Significance
$X_1 \rightarrow Y$	-0.356	3.408	0.001	0.706	Significant
$X_2 \rightarrow Y$	0.169	1.914	0.056		Not Significant
$X_3 \rightarrow Y$	0.336	2.707	0.007		Significant
$X_4 \rightarrow Y$	0.255	2.729	0.006		Significant

The results of the structural model analysis using the PLS-SEM approach indicate that the independent variables X_1, X_3, and X_4 have a significant effect on the dependent variable (Y). The structural model shows that X_1 has a negative effect on Y, with a path coefficient of -0.356, whereas X_2, X_3, and X_4 have positive effects, with path coefficients of 0.169, 0.336, and 0.255, respectively. The R^2 value of 0.706 indicates that the combination of the independent variables explains 70.60% of the variance in the dependent variable.

Government support (X_1) has a significant negative effect on farmer effectiveness in using combine harvesters (Y), with a path coefficient of -0.356, a t-statistic of 3.408, and a p-value of 0.001. Programs, regulations, and facilitation for the development and utilization of combine harvesters are already available, structured according to farmers' needs, and designed for sustainable implementation (Ibrahim and Truby, 2023; Lowenberg-DeBoer et al., 2022). However, their implementation remains suboptimal due to low farmer participation, highlighting the need for additional support from agricultural extension services (Becerra-Encinales et al., 2024; Brown et al., 2021).

The government has established combine harvester development programs, including the Agricultural Mechanization Provision and Utilization Program, and the Bank Credit Assistance Scheme for Purchasing Agricultural Machinery (Kredit Usaha Tani) for farmers. Regulatory support has been issued in the form of norms, standards, procedures, and criteria, accompanied by technical guidance and supervision for postharvest improvement using mechanization. Facilitative support is provided through the provision of combine harvesters to agricultural institutions such as farmer groups and Agricultural Machinery Service Units.

Based on interviews with agricultural extension officers and farmers in Cikedung Subdistrict, Indramayu Regency, it was found that government facilitation in the form of combine harvester provision has not adequately met farmers' needs during rice harvests, which cover a total of 7,669 ha of paddy fields. To meet the demand for combine harvesters during harvest, farmers often rent machines from mechanization service providers in other provinces, incurring higher rental costs and waiting in line for availability. Although extension officers have disseminated information regarding bank credit schemes for purchasing agricultural machinery, these programs have not yet been utilized by either farmers or agricultural institutions. Farmers perceive combine harvesters as expensive and unaffordable, even with access to credit schemes, and therefore rely on renting from private providers. These conditions indicate that government support has not become the primary factor driving the adoption of combine harvesters among farmers. Available government programs, regulations, and facilitation are considered insufficient to meet farmers' needs, resulting in greater reliance on private services. Consequently, in the context of this study, government support exhibits a negative effect on farmer effectiveness in utilizing combine harvesters.

The availability and accessibility of combine harvesters (X_2) were found to have no statistically significant effect on farmer effectiveness in using combine harvesters (Y), with a path coefficient of 0.169, a t-statistic of 1.914, and a p-value of 0.056. This result indicates that although most farmers have access to combine harvester technology, its utilization has not yet reached an optimal level. This situation is likely due to several constraints, including the limited number of available units, uneven distribution, and the need to improve the technical skills of both farmers and operators (Bisheko and Rejikumar, 2023; Khan et al., 2024). In Indramayu Regency, the availability of combine harvesters remains limited, forcing farmers to rely on mechanization service providers from Central Java. This dependence creates access difficulties, as farmers must wait in queues to rent the machinery. More than 50% of food crops are produced by smallholder farmers who have limited capital to purchase mechanization equipment. Moreover, banks are generally reluctant to provide unsecured credit for agricultural investment, as the sector is considered high-risk. Consequently, farmers are highly dependent on government support for mechanization provision.

However, government budget allocations for mechanization procurement are very limited. As a result, the availability of agricultural machinery cannot meet farmers' needs, prompting them to rent equipment from private providers (Paman et al., 2016; Sims and Kienzle, 2017; van Loon et al., 2020). The limited availability of combine harvesters in Indramayu continues to restrict access, reinforcing farmers' reliance on external mechanization service providers.

Land and crop characteristics (X_3) have a positive and significant contribution to farmer effectiveness in using combine harvesters (Y), with a path coefficient of 0.336, a t-statistic of 2.707, and a p-value of 0.007. These results indicate that land and crop characteristics play an important role in enhancing farmers' effectiveness in using combine harvesters, with a significance level of 99%. Therefore, land and crop characteristics can be considered a key factor in strategies aimed at improving combine harvester utilization. This finding aligns with the observations of Emran et al. (2022), Fischetti et al. (2025), Terán-Samaniego et al. (2025), and Mouratiadou et al. (2024), who stated that agroecological characteristics and crop types strongly determine farm productivity and operational efficiency.

Agricultural institutional support (X_4) also shows a positive and significant effect on farmer effectiveness in using combine harvesters (Y), with a path coefficient of 0.255, a t-statistic of 2.729, and a p-value of 0.006. This result suggests that agricultural institutions are a relevant and effective predictor for enhancing combine harvester utilization. Policies aimed at strengthening the capacity of agricultural institutions, such as farmer groups, Agricultural Extension Centers, and Agricultural Machinery Service Units, have been shown to promote broader adoption of innovation and agricultural mechanization.

The dynamics of farmer groups play a crucial role in strengthening social cohesion among farmers, facilitating information dissemination, and improving access to resources and technology, including combine harvesters. In this context, agricultural extension services serve as a central bridge between policy and field practice through extension activities, technical training, and intensive, locally tailored support for farmers. Meanwhile, the presence of Mechanization Service Units as a mechanization service institution provides critical operational and technical support that ensures the sustainable utilization of agricultural machinery (Wu et al., 2025).

3.5. Discussion: Model and strategy for enhancing combine harvester utilization

The model and strategy for enhancing combine harvester utilization were developed based on the results of verification and performance tests under varying field conditions (technical aspects), as well as the description of research variables and PLS-SEM model analysis (social aspects). The prioritization in formulating strategies was determined based on the highest variable coefficients and the lowest indicator category values, thereby exerting the greatest influence on increasing combine harvester usage. The model for improving combine harvester utilization, supported by farmer effectiveness, is presented in Fig. 3.

Based on Fig. 3, the priority strategies for enhancing the implementation of combine harvesters are identified as follows:

1. Improving field and farm road conditions. Field improvements can be achieved by enhancing rice paddy drainage, while the improvement of farm roads aims to facilitate combine harvester access to the fields.

2. Using appropriate rice varieties and planting patterns compatible with combine harvester operations. The use of lodging-resistant rice varieties with a plant height of approximately 80–120 cm allows the combine harvester to cut the rice stalks efficiently. In addition, implementing an optimal planting density of around 30–40 clumps per m^2 ensures harvesting efficiency and minimizes yield loss.
3. Strengthening the capacity of agricultural institutions, including farmer groups, agricultural extension institutions, and mechanization service units. Institutional strengthening can be achieved through facilitation of combine harvester access, technical training, and ongoing guidance and supervision from the Ministry of Agriculture and local Agricultural Offices.
4. Improving the facilitation of combine harvester assistance according to farmers' needs. Government support in the form of combine harvester units should be distributed through farmer-based institutions such as farmer groups, farmer group associations, and mechanization service units. This targeted assistance is essential for increasing the availability and accessibility of combine harvesters in rural farming communities.
5. Increasing the intensity of program and regulatory dissemination regarding the development and use of combine harvesters. Dissemination can be conducted in a tiered manner by the Ministry of Agriculture, local Agricultural Offices, and Agricultural Extension Centers.

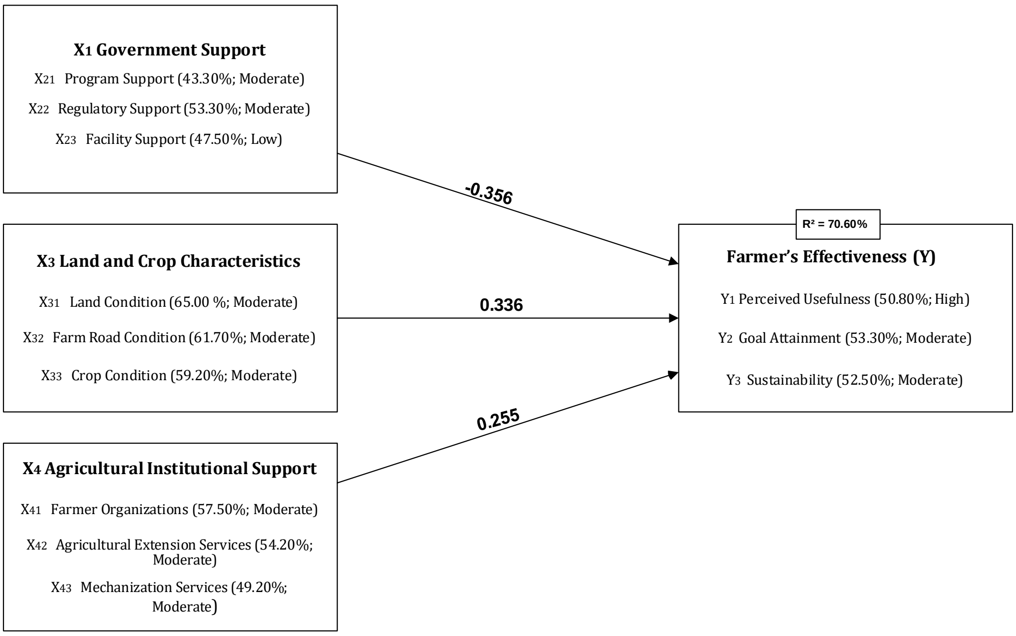

Fig. 3: Model for enhancing combine harvester utilization supported by the farmer's effectiveness

4. Conclusion

Based on the verification tests, the combine harvester was found to comply with the applicable standards in terms of capacity, quality, efficiency, and operational safety. Performance tests indicated that field conditions influenced operational ease, which correlated with postharvest losses. The combine harvester achieved an efficiency of 63.57% on medium-depth fields and 68.11% on shallow fields. The average postharvest loss was 2.08 kg, with a header loss of 0.009% and a threshing loss of 0.001%. Therefore, the combine harvester meets the requirements of INS 8185:2019 for multi-commodity harvesting machines. PLS-SEM analysis revealed that government support, land and crop characteristics, and agricultural institutional support were the most significant factors influencing farmers' effectiveness in using combine harvesters, collectively accounting for 70.60% of the variance. Accordingly, strategies to enhance combine harvester utilization supported by farmers' effectiveness include: improving field and farm road conditions; using appropriate rice varieties and implementing planting patterns suitable for combine harvester operations; strengthening the capacity of farmer groups, agricultural extension institutions, and mechanization service units; improving the facilitation of combine harvester assistance according to farmers' needs; and enhancing the intensity of program and regulatory dissemination on the development and use of combine harvesters.

Acknowledgment

The authors would like to express their appreciation to all parties who contributed and provided them with the opportunity to complete this research. They extend special gratitude to the Head of the Agricultural Extension and Human Resource Development Agency, the Head of the Agricultural Education Center of the Ministry of Agriculture, and the Director of the Bogor Agricultural Development Polytechnic for providing the facilities and financial support.

Compliance with ethical standards

Ethical considerations

Adult respondents were selected based on the research design and predetermined inclusion criteria. Prior to data collection, respondents were informed about the purpose, intent, and expected outcomes of the study. All personal data was anonymized, treated confidentially, and used solely for research purposes.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Abdalla OA, Dahab MH, Musa MM, and Babikir ESN (2021). Influence of combine harvester forward and reel speeds on wheat harvesting losses in Gezira scheme (Sudan). International Journal of Scientific Advances, 2(2): 177-182. https://doi.org/10.51542/ijscia.v2i2.17

Ahmad MT and Khadzir MK (2024). Performance evaluation of a height adjustable mini combine harvester. Advances in Agricultural and Food Research Journal, 5(1): a0000405. https://doi.org/10.36877/aafrj.a0000405

Akter H, Ali MR, Alam MS, Sarker TR, Ahamed S, and Saha CK (2024). Estimation of economic life and feasibility of combine harvesters in Bangladesh deploying a unique web-based app. Smart Agricultural Technology, 7: 100378. https://doi.org/10.1016/j.atech.2023.100378

Amrullah ER and Pullaila A (2019). The impact of combine harvester utilization on loss of rice yields in Banten Province. Jurnal Agro Ekonomi, 37(2): 113-122. https://doi.org/10.21082/jae.v37n2.2019.113-122

Arsyad S, Mursalim, and Azis A (2025). Utilization management of government-assisted combined harvester in Wajo Regency (a case study of Takkalalla and Bola districts). IOP Conference Series: Earth and Environmental Science, 1471: 012067. https://doi.org/10.1088/1755-1315/1471/1/012067

Becerra-Encinales JF, Bernal-Hernandez P, Beltrán-Giraldo JA, Cooman AP, Reyes LH, and Cruz JC (2024). Agricultural extension for adopting technological practices in developing countries: A scoping review of barriers and dimensions. Sustainability, 16(9): 3555. https://doi.org/10.3390/su16093555

Bisheko MJ and Rejikumar G (2023). Major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia: A systematic literature review. World Development Sustainability, 2: 100070. https://doi.org/10.1016/j.wds.2023.100070

Blas R, Laurente AJC, Vivar AD, and Lopez JM (2022). Farmers'acceptability on using combined harvester in San Miguel, Bulacan, Philippines. In the Proceeding Economy of Asia International Conference, Kota Malang, Indonesia: 476-483.

Brown B, Paudel GP, and Krupnik TJ (2021). Visualising adoption processes through a stepwise framework: A case study of mechanisation on the Nepal Terai. Agricultural Systems, 192: 103200. https://doi.org/10.1016/j.agsy.2021.103200 **PMid:34345114 PMCid:PMC8314065**

Daum T and Birner R (2020). Agricultural mechanization in Africa: Myths, realities and an emerging research agenda. Global Food Security, 26: 100393. https://doi.org/10.1016/j.gfs.2020.100393

Desrial, Fauzan ID, and Wiyono S (2024). Performance and economic evaluation of rice combine harvester in the innovation village of Subang, West Java, Indonesia. IOP Conference Series: Earth and Environmental Science, 1386: 012011. https://doi.org/10.1088/1755-1315/1386/1/012011

Diao X, Takeshima H, and Zhang X (2020). An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia? International Food Policy Research Institute (IFPRI), Washington, USA. https://doi.org/10.2499/9780896293809

Emran SA, Krupnik TJ, Aravindakshan S, Kumar V, and Pittelkow CM (2022). Impact of cropping system diversification on productivity and resource use efficiencies of smallholder farmers in south-central Bangladesh: A multi-criteria analysis. Agronomy for Sustainable Development, 42: 78. https://doi.org/10.1007/s13593-022-00795-3 **PMid:35945988 PMCid:PMC9355929**

Esgici R, Sessiz A, and Bayhan Y (2016). The relationship between the age of combine harvester and grain losses for paddy. Mechanization in Agriculture & Conserving of the Resources, 62(1): 18-21.

Fischetti E, Beni C, Santangelo E, and Bascietto M (2025). Agroecology and precision agriculture as combined approaches to increase field-scale crop resilience and sustainability. Sustainability, 17(3): 961. https://doi.org/10.3390/su17030961

Fu J, Ji C, Liu H, Wang W, Zhang G, Gao Y, Zhou Y, and Abdeen MA (2022). Research progress and prospect of mechanized harvesting technology in the first season of ratoon rice. Agriculture, 12(5): 620. https://doi.org/10.3390/agriculture12050620

Gebiso T, Ketema M, Shumetie A, and Feye GL (2024). Impact of farm mechanization on crop productivity and economic efficiency in central and southern Oromia, Ethiopia. Frontiers in Sustainable Food Systems, 8: 1414912. https://doi.org/10.3389/fsufs.2024.1414912

Hair JF, Hult GTM, Ringle CM, and Sarstedt M (2014). A primer on partial least squares structural equation modeling (PLS-SEM). SAGE Publications, Thousand Oaks, USA.

Harel B, Edan Y, and Perlman Y (2022). Optimization model for selective harvest planning performed by humans and robots. Applied Sciences, 12(5): 2507. https://doi.org/10.3390/app12052507

Hossain MA, Hoque MA, Wohab MA, Miah MM, and Hassan MS (2015). Technical and economic performance of combined harvester in farmers field. Bangladesh Journal of Agricultural Research, 40(2): 291-304. https://doi.org/10.3329/bjar.v40i2.24569

Ibrahim IA and Truby JM (2023). FarmTech: Regulating the use of digital technologies in the agricultural sector. Food and Energy Security, 12(4): e483. https://doi.org/10.1002/fes3.483

Khan EA, Hossain MA, Jahed MA, Akter R, and Pappas IO (2024). Green strategic leadership capability: Construct development and measurement validation. Journal of Cleaner Production, 450: 141575. https://doi.org/10.1016/j.jclepro.2024.141575

Lashgari M, Mobli H, Omid M, Alimardani R, and Mohtasebi SS (2008). Qualitative analysis of wheat grain damage during harvesting with John Deere combine harvester. International Journal of Agriculture and Biology, 10(2): 201-204.

Li H and Xu L (2022). Research on key technologies of planting machinery and combine harvester. Agronomy, 12(12): 3177. https://doi.org/10.3390/agronomy12123177

Liu P, Wang X, and Jin C (2023). Research on the adaptive cleaning system of a soybean combine harvester. Agriculture, 13(11): 2085. https://doi.org/10.3390/agriculture13112085

Lowenberg-DeBoer J, Behrendt K, Ehlers MH et al. (2022). Lessons to be learned in adoption of autonomous equipment for field crops. Applied Economic Perspectives and Policy, 44(2): 848-864. https://doi.org/10.1002/aepp.13177

Malanon HG and Pabuayon IM (2022). Pattern and determinants of rice combine harvester adoption in Isabela, Philippines. Asian Journal of Applied Sciences, 10(5): 451-463. https://doi.org/10.24203/ajas.v10i5.7050

Mouratiadou I, Wezel A, Kamilia K, Marchetti A, Paracchini ML, and Bàrberi P (2024). The socio-economic performance of agroecology: A review. Agronomy for Sustainable Development, 44: 19. https://doi.org/10.1007/s13593-024-00945-9

Myeni L, Moeletsi M, Thavhana M, Randela M, and Mokoena L (2019). Barriers affecting sustainable agricultural productivity of smallholder farmers in the Eastern Free State of South Africa. Sustainability, 11(11): 3003. https://doi.org/10.3390/su11113003

Olasehinde-Williams G, Adedoyin FF, and Bekun FV (2020). Pathway to achieving sustainable food security in sub-Saharan Africa: The role of agricultural mechanization. Journal of Labor and Society, 23(3): 349-366. https://doi.org/10.1111/wusa.12483

Paman U, Inaba S, and Uchida S (2016). Economic aspects of machinery hire services managed by farmer groups Inkampar Regency, Indonesia. Applied Engineering in Agriculture, 32(2): 169-179. https://doi.org/10.13031/aea.32.11263

Saputra H (2021). Technical, financial and social cultural of feasibility analysis of combine harvester in rice agribusiness in Tulang Bawang District, Lampung Province. Journal of Global Sustainable Agriculture, 1(2): 46-55. https://doi.org/10.32502/jgsa.v1i2.3212

Sarkar P, Raheman H, and Sahoo AU (2025). Field performance evaluation and economic analysis of an electric cabbage harvester suitable for small farms. Discover Agriculture, 3: 15. https://doi.org/10.1007/s44279-025-00156-0

Sims B and Kienzle J (2017). Sustainable agricultural mechanization for smallholders: What is it and how can we implement it? Agriculture, 7(6): 50. https://doi.org/10.3390/agriculture7060050

Tang Z, Li Y, and Cheng C (2017). Development of multi-functional combine harvester with grain harvesting and straw baling. Spanish Journal of Agricultural Research, 15(1): e0202. https://doi.org/10.5424/sjar/2017151-10175

Terán-Samaniego K, Robles-Parra JM, Vargas-Arispuro I et al. (2025). Agroecology and sustainable agriculture: Conceptual challenges and opportunities: A systematic literature review. Sustainability, 17(5): 1805. https://doi.org/10.3390/su17051805

van Loon J, Woltering L, Krupnik TJ, Baudron F, Boa M, and Govaerts B (2020). Scaling agricultural mechanization services in smallholder farming systems: Case studies from sub-Saharan Africa, South Asia, and Latin America. Agricultural Systems, 180: 102792. https://doi.org/10.1016/j.agsy.2020.102792 **PMid:32255893 PMCid:PMC7063696**

Wang K, Xie R, Ming B, Hou P, Xue J, and Li S (2021). Review of combine harvester losses for maize and influencing factors. International Journal of Agricultural and Biological Engineering, 14(1): 1-10. https://doi.org/10.25165/j.ijabe.20211401.6034

Winarno K, Sustiyo J, Aziz AA, and Permani R (2025). Unlocking agricultural mechanisation potential in Indonesia: Barriers, drivers, and pathways for sustainable agri-food systems. Agricultural Systems, 226: 104305. https://doi.org/10.1016/j.agsy.2025.104305

Wu Z, Liao B, Fu Q, Qi C, and Liao W (2025). Agricultural machinery adoption and farmers' well-being: Evidence from Jiangxi Province. Agriculture, 15(7): 738. https://doi.org/10.3390/agriculture15070738

Zhu X, Chi R, Du Y, Qin J, Xiong Z, Zhang W, and Li X (2020). Experimental study on the key factors of low-loss threshing of high-moisture maize. International Journal of Agricultural and Biological Engineering, 13(5): 23-31. https://doi.org/10.25165/j.ijabe.20201305.5653