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RESEARCH ARTICLE
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A Comparative Stochastic Analysis of Rice Farmers' Income Potential across Cultivation Systems toward Achieving Regional Minimum Wage Standards

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ABSTRACT

Rice production in Indonesia has declined due to shifting farmer preferences and increasingly adverse agricultural conditions, prompting many to pursue non-agricultural livelihoods. In this context, North Aceh Regency introduced advanced rice cultivation technologies. Despite these efforts, not all systems guarantee incomes above the Regional Minimum Wage (RMW). This study, therefore, estimates the likelihood that North Aceh rice farmers, represented by those from five sub-districts—Baktiya, Baktiya Barat, Muara Batu, Nisam, and Syamtalira Bayu—can achieve or exceed the RMW. Using quota sampling, farmers were selected from each cultivation system in the sub-districts until quotas were met, resulting in 180 respondents (45 per system). Data on yield, production cost, and grain prices were collected from these farmers between 2019 and 2022, yielding 540 data points. The stochastic variables analyzed included yield, price, and production cost. To model income variability and account for uncertainty, Monte Carlo simulations with 5,000 iterations were conducted in Microsoft Excel 2019, applying a 95% confidence interval. The results indicate that systems employing certified seeds, optimized plant spacing (2:1 and 3:1), three-stage fertilization, and systematic weeding provide a very high probability (around 99–100% probability of meeting or exceeding the RMW both seasonally and annually. Conversely, systems using only local or certified seeds show a 0–1% probability, while certified seeds combined with fertilizer yield approximately 40%. These findings underscore the need for targeted interventions—such as certified seed programs, optimized spacing, balanced fertilization, and farmer training—to improve income security and enhance rural economic resilience in North Aceh.

Keywords: Rice production, Cultivation systems, Farmers' income, Regional Minimum Wage, Monte Carlo simulation.

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INTRODUCTION

Rice (Oryza sativa) is a major Indonesian commodity and staple food. In 2022/2023, Indonesia ranked fourth worldwide in rice production, after China, India, and Bangladesh (Zumrotun, 2023). Despite this, most rice farmers remain poor. They face constraints such as small land ownership (under 0.5ha), inadequate access to land and infrastructure, minimal irrigation, and low adoption of technology. These factors limit productivity and income (Widyanto & Subanu, 2023). Additionally, low rice prices and suboptimal productivity exacerbate the financial pressures faced by farmers (Antara et al., 2023; Makbul et al., 2021).

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Aceh Province has strong potential to support national food security, especially through North Aceh Regency. This area is the largest rice producer in the province. North Aceh has a harvested area of 54,723ha and produces 318,432ton of rice. The regency records a productivity of 5.81ton/ha (Statistik, 2023). However, this is 5.81ton/ha below the national standard of 7ton/ha. This gap highlights the need for improvements in agronomy and cultivation systems.

The government has undertaken various efforts to increase production. These include outreach programs on the use of certified superior seeds, balanced and efficient fertilization, pest and disease control, and new planting systems such as Jajar Legowo and the System of Rice Intensification (SRI). The Jajar Legowo system regulates plant spacing. It increases plant population, improves light penetration, and reduces labor costs by allowing the use of rice transplanters (Galingging et al., 2024; Purwanto et al., 2023; Yusuf, 2024). This system is expected to increase crop yields and raise farmer income. Selecting plant varieties and using certified seeds are also important for successful cultivation (Prasetyo et al., 2022).

Genotype plays a crucial role in crop systems. It affects yield, pest and disease resistance, and climate adaptation (Prasetyo et al., 2022). The government urges farmers to use fertilizers appropriately and efficiently. Studies have found that accurate doses significantly increase yields (Effendi et al., 2023; Suyanto et al., 2023; Nelvia et al., 2024). Still, many farmers use suboptimal dosages due to limited capital or inadequate knowledge. Excessive fertilizer can harm soil by causing salt buildup and compaction. This degrades soil quality over time (Supriyadi et al., 2021; Suyanto et al., 2023). Organic fertilizers are seen as more efficient. They can lower production costs (Salam et al., 2021; Rahmawati et al., 2025). Several rice cultivation systems have been developed through extension programs and technology adaptations. Farmers in North Aceh Regency have adopted these to improve production efficiency and income. However, low grain prices during the main harvest often cause farmer incomes to fall below production costs. This shows current systems do not fully address post-harvest income risks.

Recent research highlights the growing importance of integrating certified seed adoption, efficient cropping systems, fertilizer optimization, and labor income considerations to strengthen rice productivity and farmer well-being in Southeast Asia. The introduction of climate-resilient, certified rice varieties has significantly increased yield potential and climate risk adaptation in smallholder systems (Mamun et al., 2024). Persistent yield disparities across the region—particularly in Cambodia, Myanmar, the Philippines, and Thailand—underscore the need for technology and fertilizer optimization, while Indonesia and Vietnam face stagnant yields insufficient to meet domestic demand (Yuan et al., 2022). Empirical evidence also shows that the Jajar Legowo cropping system increases rice yields and farm incomes by approximately 12% compared to conventional practices (Prasetyo, 2023), while the System of Rice Intensification (SRI) faces practical challenges due to high labor and input requirements (Arsil et al., 2022).

Labor market interactions remain central to smallholder farmers' well-being. Vocational training and awareness of minimum wage policies significantly increase agricultural labor incomes by USD 3–5 per month. However, informal contracts often limit access to social protection (Thi & Ninh, 2021). Despite ongoing modernization, agricultural incomes in Indonesia remain weak, and farmers' terms of trade for food crops remain low (Sukma et al., 2025). A broader analysis of agricultural transitions in Southeast Asia suggests that most changes increase income and employment opportunities but can also create trade-offs with welfare and well-being (Appelt et al., 2022).

However, existing research rarely measures how production system choices affect farmers' ability to meet income thresholds under conditions of illness. Food crop farmers in Indonesia—particularly rice farmers in North Aceh, the largest rice-producing district in Aceh, Indonesia—often live below the Regional Minimum Wage (UMR) (Fatwa et al., 2022; Iklillah et al., 2023), and the district's poverty rate remains high at 16.86% (Sammy, 2023).

This study complements this analysis by estimating the probability that rice farmers in North Aceh earn the minimum wage (USD 220.43 per month, USD 2,645.16 per year) across four cultivation systems. The study uses Monte Carlo simulations to assess the likelihood of achieving farmer incomes equal to or above the minimum wage, accounting for price and yield variability. The analysis compares the effectiveness of each system in helping farmers achieve the minimum wage and identifies the most resilient production approaches. The results provide empirical evidence to support policies related to certified seed programs, fertilizer optimization, and minimum wage implementation, as well as farm management strategies that enhance income security and sustainable development.

MATERIALS & METHODS

Research Location

This research was conducted in North Aceh Regency, Aceh Province, a region renowned for its rice production. The North Aceh Agriculture Service recommended this location because farmers in different sub-districts employ four distinct rice cultivation systems. Therefore, the research selected Baktiya Barat District, Muara Batu District, Nisam District, and Syamtalira Bayu District to each represent one of these cultivation systems (Fig. 1). The research activities spanned six months, from January to June 2023.

Research Design and Sampling

Population and Sampling Techniques

This study employed a quota sampling approach to ensure proportional representation of each rice cultivation system practiced in North Aceh Regency. The choice of quota sampling was based on the uneven geographical distribution of cultivation systems and the impracticality of defining a full sampling frame across all sub-districts.

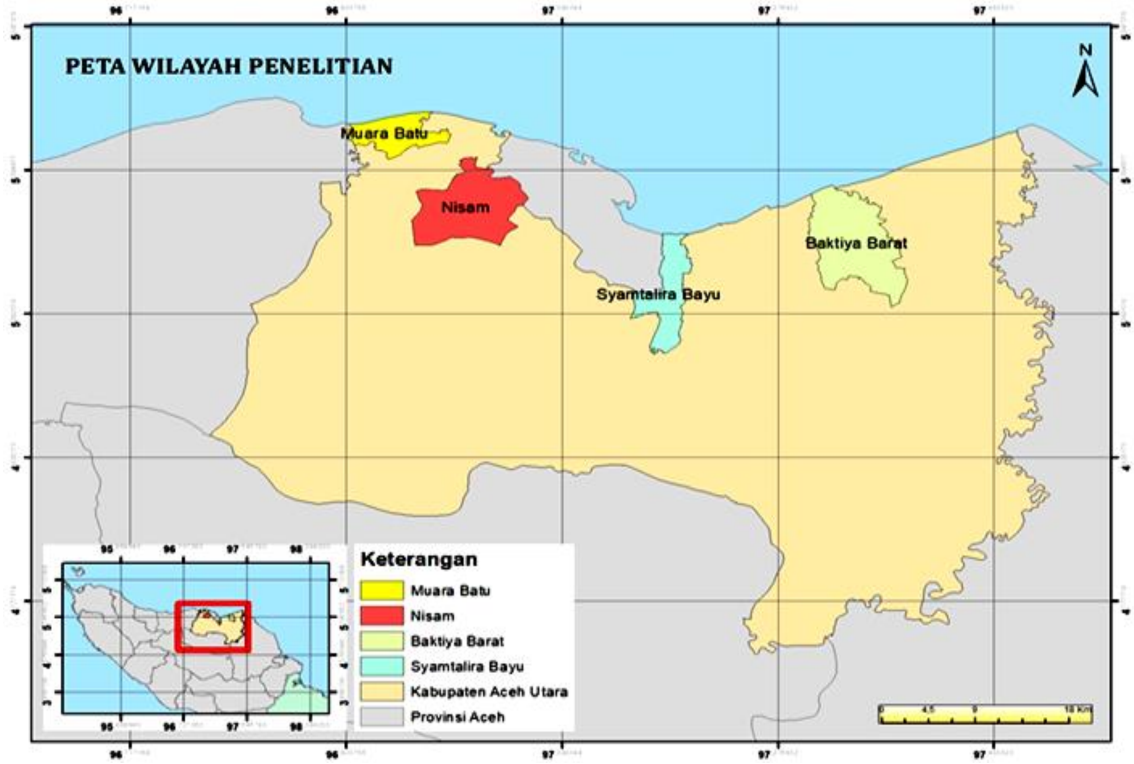

Fig. 1: Map of Indonesia, North Aceh Districts.

Quota sampling was chosen because it allows the researcher to select participants from predefined sub-groups when a complete sampling frame is unavailable or when system distribution is clustered geographically (Futri et al., 2022; Kim, 2022). However, because participants are non-randomly selected within each quota, the method does not permit calculation of sampling error or full generalisation to the broader population, and selection bias must therefore be acknowledged and managed (Futri et al., 2022). By using quotas, the study was able to target specific systems that are otherwise clustered in particular locations, while still enabling intra-system comparisons. While non-probability in nature, quota sampling remains an acceptable method when random selection is infeasible in field settings; the limitations of this method — including potential selection bias and limited generalizability — have been explicitly acknowledged (see Section "Limitations and Data Availability").

Five sub-districts were purposively selected: Muara Batu, Nisam, Syamtalira Bayu, Baktiya, and Baktiya Barat. These locations were chosen based on a preliminary survey which identified the presence and relative frequencies of the four target cultivation systems. The mapping between sub-districts and cultivation systems is shown in Table 1.

For each cultivation system, 45 eligible farmers were selected, resulting in a total sample of N = 180 farmers (45 per system). These farmers had continuously cultivated rice under their respective systems for the cropping years 2019–2022 (three years).

Eligibility criteria included:

1. Being an active rice farmer in North Aceh during 2019–2022.
2. Applying the same cultivation system consistently for three consecutive cropping seasons.
3. Owning or managing land of less than 2.0 ha (to focus on smallholder conditions).

Regarding data collection, yields, input costs, and income were collected through structured interviews using validated questionnaires. The data were primarily self-reported by farmers, but each record was cross-checked with production logs held by local agricultural extension offices and farmer group records to enhance reliability.

Because plot sizes varied substantially (0.1 ha to 2.0 ha), we standardised income to $/ha. This normalisation ensured that comparisons across systems focused on productivity and management efficiency rather than simply larger landholdings. Additionally, we examined whether the average plot size differed significantly among systems, and found no systematic bias in mean size by system.

Table 1: Cultivation System Mapping

Cultivation System	Sub-districts Selected
Cultivation System 1 – Traditional (uncertified seeds, low fertilizer, sowing, irregular weeding, no spacing adjustment)	Muara Batu, Nisam, Syamtalira Bayu, Baktiya Barat
Cultivation System 2 – Certified seed adoption, but no spacing/regulation yet	Nisam, Baktiya Barat, Baktiya, Syamtalira Bayu
Cultivation System 3 – Certified seeds + regular main fertiliser (Urea/NPK), occasional organics, no regulated spacing	Muara Batu, Nisam, Baktiya Barat
Cultivation System 4 – Optimised management (certified seeds, regulated spacing via Jajar Legowo, three-stage Urea/NPK, periodic organics)	Muara Batu, Nisam, Baktiya Barat

Analysis Method

The analytical method used in this study is the Monte Carlo simulation method, which aims to evaluate the probability of rice farmers' income in each cultivation system. This approach is used to identify cultivation systems that have the highest chance of generating net income equal to or exceeding the Regional Minimum Wage (RMW) in North Aceh Regency. Using this stochastic simulation technique, net income uncertainty is dynamically modeled to provide a more realistic estimate of farmers' economic opportunities. The dollar value is expressed using the exchange rate of IDR 15,439, as reported by Bank Indonesia on December 29, 2023 (Bank Indonesia, 2025) and the RMW value of North Aceh is IDR 3,413,666 per month, equivalent to USD 221.11, as reported by the Indonesian Ministry of Manpower and confirmed by Bank Indonesia's exchange rate data on December 29, 2023 (Kompas.com, 2024).

Monte Carlo Simulation

The analysis method used in this study is a Monte Carlo simulation, which aims to evaluate the probability distribution of farmers' net income based on the applied Cultivation system, as well as identifying opportunities for farmers' income to be equal to or greater than the Regional Minimum Wage (RMW). The analysis procedure is carried out in stages through the following stages, as carried out by (Kadigi et al., 2020):

1. Definition of Stochastic Variables
The main variable used in the simulation is net income (NCL). To obtain NCL data on rice per ha ($\tilde{y}_i$), land area (a_i), and rice selling price (p_i), the total cost per planting season, all values of which are obtained from the survey results, is calculated before the simulation.
2. MVE (Mean Value Estimate) Simulation Procedure
The MVE represents the average (expected) value of an output variable that results from repeated Monte Carlo simulations. The MVE simulation was performed for 5,000 iterations to obtain a stable income distribution that reflects the income opportunities contained in the data. Stochastic sampling was used to ensure the simulation results were representative and usable for decision-making.
3. Simulation Distribution Validation
The simulation distribution is compared with the observed data to ensure the distribution conforms to its shape. This step is essential to verify that the random variables have been simulated correctly and follow a normal distribution that can be analyzed statistically.
4. Stochastic Net Income Distribution
Net Income is varied stochastically using a probability distribution. This distribution allows estimation of Net Income using three subjective approaches: standard deviation, realistic (average/model), and optimistic (maximum). The simulation is performed using Excel to generate random costs based on technical choices commonly used by small-scale farmers. Equation (7)

Actual yield of farmers with cultivation system i (ton/ha) from observations

$$\tilde{y}_i = y_i \tag{1}$$

Actual price of farmers with cultivation system i ($/ton) from observations

$$\widetilde{P_{wi}} = P_{wi} \tag{2}$$

Total production of farmers with cultivation system i (ton), the product of actual yield and land area

$$\tilde{\mu}_i = \tilde{y}_i * a_i \tag{3}$$

Income of farmers with cultivation system i ($/season)

$$\tilde{R}_i = \widetilde{P_{wi}} * \tilde{\mu}_i \tag{4}$$

Production cost of farmers with cultivation system i ($/season) based on actual observed data

$$\tilde{C}_i = C_i \tag{5}$$

Net Cash Level of farmers with cultivation system i ($/season) based on actual observed data 2019–2022

$$\widetilde{NCL\_}i = \tilde{R}_i - \tilde{C}_i \tag{6}$$

Net Cash Level of farmer i, *which can be analyzed through Monte Carlo simulation to assess risk and the probability of income exceeding the Required Minimum Wage (RMW)*

$$\widetilde{NCL}_i = Distribution\ (SD_{vi}, Average_{vi}, Max_{vi}) \tag{7}$$

Where:
~ : Stochastic Variable
I : Cultivation techniques (cultivation techniques 1, 2, 3, and 4)
$\tilde{y}_i$: Stochastic yield of rice per (ha) in each cultivation technique
a_i : Hectares (ha) in each cultivation technique
$\widetilde{NCL}_i$: Stochastic production in cultivation techniques
$\widetilde{P_w}$: Rice prices are influenced by the season
$\tilde{R}_i$: Revenue, which is stochastic production and price
$\tilde{C}_i$: Total production costs in each cultivation technique

RESULTS

Rice Production Data

North Aceh Regency is the highest rice-producing region in Aceh. In North Aceh, farmers typically plant twice a year, but some only plant during the rainy season. Below are rice production figures in North Aceh Regency over the past three years.

Based on Table 2, it is evident that rice production in each cultivation system yields different results. The highest rice production results are in cultivation system 4, followed by cultivation system 3, cultivation system 2, and the lowest is cultivation system 1. The production results of cultivation systems 1 and 2 per ha in North Aceh are below the national average yield per ha, which is 5.24 ton/ha (Adi Ahdiat, 2024). Cultivation system 3 has relatively the same productivity as the national average productivity. Cultivation system 4, which provides maximum agro-input, good maintenance, and implements a spacing system such as jajar legowo, has an average productivity that exceeds national productivity.

Price of Paddy

The price of unhusked rice is a very influential indicator in determining the income that farmers will receive. The average cost of unhusked rice in North Aceh

Table 2: Data on paddy production results (ton/ha) (2019–2022, N = 180)

Cultivation system (CS)	2019/2020			2020/2021			2021/2022		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
Cultivation System 1	4.25	3.00	5.00	4.22	3.00	5.00	4.31	3.00	5.00
Cultivation System 2	4.68	3.85	5.75	4.55	3.33	5.50	4.69	3.85	5.63
Cultivation System 3	5.86	5.00	6.50	5.79	4.50	6.40	5.87	4.50	6.50
Cultivation System 4	7.36	6.00	8.00	7.26	6.00	8.67	7.41	6.00	8.67

Table 3: Selling price of paddy (2019–2022, N = 180)

Statistics	Rainy season planting ($/Kg)		Dry season planting ($/Kg)	
	Certified Seeds	Uncertified Seeds	Certified Seeds	Uncertified Seeds
Average	$0.32	$0.31	$0.35	$0.34
Min	$0.32	$0.30	$0.35	$0.34
Max	$0.32	$0.32	$0.36	$0.34
Number of Respondents	45	45	45	45

Table 4: Production costs of rice cultivation systems (2019–2022, N = 180)

	Cultivation system 1	Cultivation system 2	Cultivation system 3	Cultivation system 4
Total production cost for rainy season planting				
Average	$545.87	$564.32	$677.81	$798.57
Min	$326.01	$390.65	$435.41	$607.23
Max	$604.96	$647.71	$795.06	$921.37
Total production costs for the dry season planting season				
Average	$546.47	$565.19	$678.86	$800.78
Min	$326.01	$390.65	$424.61	$607.23
Max	$605.61	$649.87	$795.06	$921.37
Total annual production costs				
Average	$1,092.35	$1,129.51	$1,356.67	$1,599.35
Min	$652.03	$781.30	$860.02	$1,214.46
Max	$1,209.92	$1,297.58	$1,590.13	$1,842.74

in 2023 is shown in Table 3. All prices are presented in U.S. dollars, converted at an exchange rate of 1 USD equals 15,439 IDR, as reported by Bank Indonesia on December 29, 2023 (Bank Indonesia, 2025).

The price of unhusked rice is a highly influential indicator of farmers' income. Unhusked rice prices vary from season to season. During harvest season, prices are lower due to the abundant (high) rice supply, while during off-season periods, rice supplies are lower, leading to higher prices. The type of seed used also affects the selling price of unhusked rice, as the quality of the resulting grain varies.

Production Costs

The production costs incurred for each cultivation system vary. Table 4 presents the production costs for each cultivation system in North Aceh Regency.

Production cost data for each cultivation system varies. In cultivation system 1, production costs are lowest due to the small amount of weeding and fertilization costs, as in cultivation system 1, weeding and fertilization are only done once. Cultivation system 4 incurs the highest costs due to routine fertilization and weeding being done three times, and the many special treatments resulting in higher costs. Production cost data and input prices for each cultivation system include the purchase price of seeds, nursery preparation, land preparation (soil cultivation starting from repairing embankments/channels to land leveling), transplanting/seeding seeds, weeding, post-emergence pesticides, bird pest control, water control (irrigation), fertilizer, harvesting/cutting/threshing, post-harvest handling, and storage costs.

Farmer's Gross Revenue

Farming income is the product of production volume and selling price. To find out the gross revenue of rice farmers in North Aceh Regency, see the table below.

Table 5 highlights that rice cultivation systems in North Aceh Regency differ mainly in their production costs, with System 1 characterized by the lowest expenses due to minimal technical activities, and System 4 by the highest costs due to intensive treatment and specialized agronomic practices. Each system's production cost includes seed purchase, nursery and land preparation, seed planting, weeding, pesticide use, irrigation management, fertilization, harvesting, post-harvest handling, and storage. The key distinction among these systems is that more frequent and higher-quality cultivation treatments result in greater investment costs compared to less intensive systems.

Farmers' Income

Farmers' income is the revenue minus production costs. The dry season in North Aceh begins in April and ends in August, while the rainy season begins in September and ends in December. Table 6 below shows farmers' income in the North Aceh district for each planting season and year, based on the cultivation system.

Table 6 shows that farmers' income varies based on their cultivation system. System 1 has the lowest average, minimum, and maximum incomes in rainy, dry, and annual seasons. Systems 2 and 3 have higher incomes, while System 4 has the highest annual income among them.

Monte Carlo Simulation Results

Monte Carlo simulation is a mathematical technique used to predict the outcome of uncertain events. Based on the Monte Carlo simulation, the field data processing results for the four cultivation systems are presented in Table 7. In this Monte Carlo simulation, we attempted to estimate the probability that each cultivation system would yield farmers' income exceeding the monthly RMW in their area.

Table 5: Farmer's gross revenue (2019–2022, N = 180)

	Cultivation system 1	Cultivation system 2	Cultivation system 3	Cultivation system 4
Farmer gross revenue in the 2019/2020 cropping year				
Average	$2,746.17	$3,142.28	$3,948.10	$4,979.91
Min	$2,247.55	$2,697.07	$3,526.78	$4,359.09
Max	$3,028.05	$3,573.74	$4,289.46	$5,307.18
Farmer gross revenue in the 2020/2021 cropping year				
Average	$2,725.68	$3,055.12	$3,902.98	$4,915.06
Min	$2,228.12	$2,551.98	$3,348.66	$4,200.40
Max	$3,095.52	$3,503.03	$4,210.12	$5,537.92
Farmer gross revenue in the 2021/2022 cropping year				
Average	$2,781.28	$3,144.37	$3,953.62	$5,019.78
Min	$2,247.55	$2,726.86	$3,517.07	$4,566.36
Max	$3,028.05	$3,581.84	$4,244.93	$5,440.77

Table 6: Farmers' income (2019–2022, N = 180)

	Cultivation system 1	Cultivation system 2	Cultivation system 3	Cultivation system 4
Farmer Income in Rainy Season Planting				
Average	$834.68	$991.48	$1,284.19	$1,685.31
StdDev	$133.27	$156.39	$140.40	$115.16
Min	$631.52	$652.24	$879.27	$1,273.72
Max	$1,190.17	$1,414.03	$1,559.77	$2,018.70
Farmer Income in Dry-Season Planting				
Average	$824.02	$992.93	$1,294.05	$1,686.92
StdDev	$148.10	$147.92	$158.34	$157.06
Min	$430.08	$647.71	$808.02	$1,305.14
Max	$1,109.20	$1,339.14	$1,554.50	$2,050.00
Annual Farmer Income				
Average	$1,658.70	$1,984.41	$2,578.23	$3,372.23
StdDev	$259.40	$289.85	$281.87	$227.77
Min	$1,068.72	$1,396.46	$1,842.74	$2,621.93
Max	$2,299.37	$2,753.17	$3,107.39	$3,961.83

Table 7: Monte Carlo simulation results

Cultivation system	Average	SD	CV	Min	Max	Probability
Income During Rainy Season Planting (per ha per season)						
Cultivation system 1	$834.68	$133.27	0.16	$631.52	$1,190.17	0.00
Cultivation system 2	$991.48	$156.39	0.16	$652.24	$1,414.03	0.02
Cultivation system 3	$1,284.19	$140.40	0.11	$879.27	$1,559.77	0.38
Cultivation system 4	$1,685.31	$115.16	0.07	$1,273.72	$2,018.70	1.00
Revenue During Dry Season Planting (per ha per season *)*						
Cultivation system 1	$824.02	$148.10	0.18	$430.08	$1,109.20	0.00
Cultivation system 2	$992.93	$147.92	0.15	$647.71	$1,339.14	0.02
Cultivation system 3	$1,294.05	$158.34	0.12	$808.02	$1,554.50	0.43
Cultivation system 4	$1,686.92	$157.06	0.09	$1,305.14	$2,050.00	0.99
*Annual net income (*per ha per year*)*						
Cultivation system 1	$1,658.70	$259.40	0.16	$1,068.72	$2,299.37	0.00
Cultivation system 2	$1,984.41	$289.85	0.15	$1,396.46	$2,753.17	0.01
Cultivation system 3	$2,578.23	$281.87	0.11	$1,842.74	$3,107.39	0.39
Cultivation system 4	$3,372.23	$227.77	0.07	$2,621.93	$3,961.83	1

The monthly RMW in North Aceh is $221.11. We calculated the probability that the income during the rainy season planting season is greater than or equal to 6 times $1,326.64. Similarly, for the dry season planting, we calculated the probability that income would exceed the equivalent RMW threshold for that season. Finally, to calculate the probability that each cultivation system's annual income is greater than or equal to the RMW, we calculated the probability that each cultivation system earns income greater than or equal to $2,653.32 per year. The likelihood that income from each cultivation system exceeds or equals the RMW is shown in the Probability column, with a 95% confidence interval.

Table 7 presents Monte Carlo simulations with a 95% confidence interval for four rice cultivation systems, evaluating income during the rainy, dry, and annual seasons. The parameters analyzed include average income, standard deviation, coefficient of variation, minimum and maximum values, and the probability of reaching or exceeding the regional minimum wage.

Cultivation System 4 had the highest average income during the rainy season, at $1,685.31 per ha per season, with a very high probability of meeting or exceeding the regional minimum wage. Cultivation System 3 had an average income of $1,294.05 per ha per season, with a low probability of meeting or exceeding the regional minimum wage. Cultivation Systems 1 and 2 had lower average incomes, making them economically unviable during the rainy season.

Cultivation system 4 generates the highest income during the dry season $1,686.92 per ha per season) with low volatility risk (CV 0.07); nevertheless, the probability of reaching the minimum wage is very high. In comparison, system 3 provides a lower income ($1,290.07 per ha per season) and a 43% chance of reaching the minimum wage. Systems 2: The probability of reaching the minimum wage is very low (2%). Meanwhile, Systems 1 continue to show low results with no chance of reaching the minimum wage.

Cultivation System 4 had the highest average annual net income of $3,372.23 per ha per year, with a very high probability, indicating that it reliably met or exceeded the regional minimum wage. System 3 had an annual revenue of $2,578.23 per ha per year with a 39% probability, meaning only 39% of simulations reached the minimum wage. Systems 1 and 2 had probabilities of 0.00 and 0.01, indicating their incomes were generally below the minimum wage.

Fig. 2 presents the probability of achieving income equivalent to or exceeding the Regional Minimum Wage (RMW) in 2023, based on variations in the selling price of unhusked rice across four rice cultivation systems. The vertical axis represents the four cultivation systems, and the horizontal axis indicates the percentage probability of attaining income at least equivalent to the RMW. The graph compares three scenarios for unhusked rice selling prices: (1) US$0.3.16 per kilogram (blue), representing the lowest certified unhusked rice price from survey results; (2) US$0.320 per kilogram (red), the average certified unhusked rice price during the survey; and (3) US$0.420 per kilogram (green), the Government Purchase Price (HPP) established by the Ministry of Administrative and Bureaucratic Reform for 2025. The results indicate that at the lowest price (US$0.316), only cultivation system 4 offers a significant probability (83%) of achieving income equivalent to the RMW. At the average price (US$0.320), this probability increases to 88% in cultivation system 4 and 3% in cultivation system 3. At the highest price (US$0.420), all systems demonstrate a substantial increase in probability: cultivation system 4 reaches very high probability, , system 3 reaches 99.10%, system 2 reaches 41.20%, and system 1 reaches 12.70%. These findings demonstrate a positive correlation between higher unhusked rice selling prices and the likelihood of farmers achieving a decent income, particularly in more productive cultivation systems.

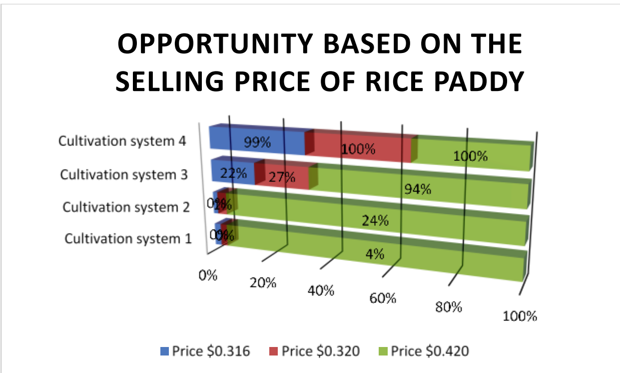

Fig. 2: Graph of opportunities to earn income equal to or exceeding RMW.

Cultivation System 1 showed no probability (0%) across all price scenarios, indicating it could not generate RMW-equivalent returns. Cultivation System 2 showed only a 41.20% probability at $0.420, and zero at lower prices ($0.316 and $0.320), indicating high price sensitivity and viability only at very high prices. Cultivation System 3 displayed positive probability at low prices—3% at $0.316 and 4% at $0.320—rising sharply to 99.10% at $0.42. This shows better economic potential than Systems 1 and 2, but ongoing vulnerability at low prices. Cultivation System 4 showed the highest, most stable probabilities: 83% at $0.316, 88% at $0.320, and 99.10% at $0.420, indicating strong economic resilience and feasibility for commercial use.

DISCUSSION

Farmers in North Aceh operate four distinct rice cultivation systems representing a gradient of intensification. System 1 remains the most traditional—relying on local seeds, unstructured spacing, single-stage fertilization, and minimal water management. While cost-efficient, this system tends to deliver the lowest productivity and income, frequently falling below the Regional Minimum Wage (RMW). In contrast, System 4 integrates certified seeds, optimized plant spacing (notably the Jajar Legowo 2:1 and 3:1 patterns), three-stage fertilization, systematic weeding, and reliable irrigation. Although this system entails higher input costs, it offers a very high probability (around 99–100%) of meeting or exceeding the RMW both seasonally and annually. Systems that rely solely on seeds (local or certified) without additional management improvements exhibit only a ~0-1% probability of achieving the income threshold.

These results are consistent with empirical literature on integrated, resource-efficient rice production systems. For example, studies on the Jajar Legowo planting pattern demonstrate improved light penetration, tiller number, and grain yields: (Karokaro et al., 2015; Prasetyo & Kadir, 2019) Illustrate yield increases of ~15–20% compared with conventional spacing. (Paiman, 2023) Provide further evidence of JL systems with organic input boosting productivity, and highlight that the 2:1 JL system offers the best balance of productivity and labor efficiency. These spacing improvements enhance the potential of fertilization and seed quality measures, thereby contributing to System 4's superior performance.

Certified seed use is a critical foundation for system intensification. Research (Sitorus et al., 2020). Shows certified seeds improve germination, uniform stands, and pest resistance; (Nurmansyah et al., 2025) Find high farmer satisfaction with certified seed programs. Yet, seed quality alone does not guarantee profitability, as studies have shown. (Haryanto et al., 2015; Siagian & Soetjipto, 2020). Find that farm-level management practices and resource inputs are essential conditions for realizing seed potential. This finding supports our conclusion that seed use without enhanced spacing, fertilization, and irrigation yields minimal benefits (hence the 0–1% probability in non-integrated systems).

Fertilization and nutrient management are also critical. (Rodriguez, 2020) Rodriguez reviews Site-Specific Nutrient Management (SSNM) strategies in Asian irrigated rice systems, demonstrating improved nutrient-use efficiency and yield stability. (Buresh et al., 2019) showed that field-specific fertilizer recommendations in the Philippines increased crop yields by approximately 17%. Building on these findings, more recent research (Purwanto et al., 2023; Rozen et al., 2023) confirmed that balanced NPK fertilization across growth stages, coupled with optimized plant spacing, further increased yields. In line with this, System 4 practices employ phased fertilization at the basal, tillering, and flowering stages, which aligns nutrient supply with crop needs and improves yield reliability.

Water management and systematic weeding complete the package of constraints removal. For instance, (Darma et al., 2025) . Show institutional responses to floods and droughts in pump-based irrigation systems in Indonesia to improve system resilience and productivity. (Tirtalistyani et al., 2022) .Highlight that ~46% of Indonesia's irrigation infrastructure is moderately to heavily damaged, limiting the effectiveness of high-input agronomic systems. Reliable irrigation and weed control reduce yield variance, ensuring that the improved seed, spacing, and fertilization can fully express their potential. Consequently, the yield floor is elevated, and the probability of achieving RMW increases.

From a socioeconomic and structural standpoint, adoption constraints are substantial. Capital limitations, small and fragmented landholdings, insufficient access to extension services, and mechanization hamper the uptake of integrated systems. (Mariyono, 2006; Prabowo et al., 2025). Risk preferences matter: many smallholders confront uncertain returns and may avoid higher-input systems despite higher expected profits. Labor availability and mechanization access are further constrained by rural-to-urban migration of agricultural workers, a trend documented in youth mobility studies. (Ngadi et al., 2025). These factors help explain why many farmers adhere to traditional systems (System 1) despite the proven advantages of intensification.

Policy instruments can help overcome these adoption barriers. Subsidies for certified seed could reduce upfront costs and increase adoption; irrigation rehabilitation programs addressing the high damage rates (46%) of irrigation infrastructure are crucial for ensuring the water reliability necessary for intensification. Price floors or guaranteed procurement schemes reduce market risk and incentivize adoption of intensified systems. Complementary investments in extension services, mechanized aids (e.g., JL transplanters), and credit for smallholders further support uptake.

Similar patterns of productivity gains from integrated systems are evident across Southeast Asia. Literature from the Philippines, Vietnam, and Thailand (Buresh et al., 2019; Rodriguez, 2020; Suweta et al., 2021) confirms that integrated packages (seed + spacing + fertilisation + irrigation) consistently outperform low-input systems. However, the magnitude of benefits depends on local agro-ecological conditions, land tenure arrangements, and institutional capacity; careful adaptation is required when transferring these practices to other contexts. Moreover, the simulation-based probability metrics used here very high probability (around 99–100%) provide a useful framework for assessing system reliability under variable smallholder conditions; however, empirical validation across seasons and sites is still needed.

In conclusion, this study reinforces a growing consensus: integrated, standardized, and resource-efficient rice cultivation systems—combining certified seeds, Jajar Legowo spacing, three-stage fertilization, systematic weeding, and reliable irrigation—substantially improve productivity and income stability in Southeast Asia. While low-input systems remain accessible and low-cost, they offer limited income security and a high risk of suboptimal resource management outcomes. The adoption of integrated systems is constrained by organizational, institutional, and resource barriers; however, supportive policies—such as seed subsidies, irrigation rehabilitation, and price floors—can facilitate scaling. By addressing both agronomic and institutional constraints, integrated systems offer a robust pathway toward achieving food security, income resilience, and progress on the Sustainable Development Goals (SDG 1: No Poverty; SDG 2: Zero Hunger; SDG 12: Responsible Production).

Conclusion

This study aims to analyze the income opportunities for rice farmers in North Aceh to equal or exceed the Regional Minimum Wage (RMW) based on four different cultivation system scenarios, using a Monte Carlo simulation model. The simulation results show that the application of agricultural technologies, such as the use of superior varieties, adequate fertilizer, and plant spacing, significantly increases crop yields and farmer income. This study has important implications for agricultural policy in Indonesia, particularly in Aceh. To improve farmer welfare and prevent career transition due to income inequality, support is needed for the adoption of more efficient cultivation technologies. These findings also emphasize the importance of maintaining the sustainability of agricultural land, particularly land areas of at least 1 ha. Without the application of modern technology, farmers are unlikely to achieve an income equivalent to the RMW. Furthermore, because optimal plant spacing can only be achieved on land with a good irrigation system, improving and monitoring irrigation infrastructure must be a top priority in agricultural development policies. Investment in farming technology and infrastructure has been proven to increase productivity and support poverty alleviation efforts through the farm sector.

Policy and Practical Implications

The findings of this study have clear implications for policy design and practical adoption strategies. System 4 demonstrates that the integration of certified seeds, Jajar Legowo (JL) spacing, staged fertilization, systematic weeding, and reliable irrigation yields the largest marginal gains in yield and income. Among these components, certified seeds provide immediate improvements in germination, uniformity, and pest resistance; JL spacing enhances light penetration, tiller number, and weed suppression; and staged fertilization stabilizes nutrient supply across crop growth stages. Reliable irrigation and consistent weeding are prerequisites to fully realizing these gains.

To facilitate adoption among smallholders constrained by capital and labor, a minimal "step-up" package is recommended for Systems 1–2. Step 1 involves adopting certified seeds, which can yield significant income improvements with a low upfront cost and a payback horizon of one cropping season. Step 2 adds JL 2:1 spacing using existing labor resources, providing an additional 15–20% yield increase with a payback horizon of one to two seasons. Step 3, staged fertilization, further enhances yield stability and moves farmers closer to the full System 4 package, with a payback horizon of two to three seasons. Implementation should prioritize sites where irrigation is reliable or rehabilitation is feasible, and consider mechanization options (e.g., JL transplanters) to reduce labor constraints.

Alignment with national programs is critical. Adoption of certified seeds supports the National Seed Program, while irrigation rehabilitation aligns with government infrastructure improvement initiatives. Price floors or guaranteed procurement schemes can mitigate market risk and encourage investment in higher-input systems. Complementary investments in extension services, farmer training, and access to credit are essential to support the step-up adoption pathway. Monitoring and evaluation should include agronomic indicators (yield, plant uniformity, tiller number, weed incidence, and fertilization timing), economic indicators (income relative to the Regional Minimum Wage, input recovery, benefit-cost ratios), and adoption metrics (uptake of certified seeds, JL spacing, and staged fertilization). Infrastructure reliability, including water supply and mechanization use, should also be tracked to ensure that the policy interventions translate into sustainable productivity and income gains. In summary, targeted, stepwise interventions—supported by national seed, irrigation, and market policies—can enable smallholders to capture the highest marginal benefits from System 4 practices while managing financial and labor constraints. This approach promotes inclusive agricultural intensification, income stability, and alignment with the Sustainable Development Goals.

Limitations and Data Availability

This study was conducted in a single region, which may limit the generalizability of the results to other regions with different agroecological and socioeconomic contexts. Some data, particularly on input use and crop yields, were obtained through direct farmer surveys and may be susceptible to recall or desirability bias. Though quota sampling allowed targeted system representation, it restricts statistical generalization to the broader population of all rice farmers in North Aceh or Indonesia. Quota sampling lacks probability-based selection, meaning sampling error and confidence intervals cannot be precisely computed. Researchers must therefore interpret findings as indicative of system comparisons rather than definitive population estimates (Stratton, 2023).

We mitigated potential biases by:

- Using a preliminary mapping survey to select sub-districts representing each system's cluster,
- Ensuring each system sample had an equal size (45) to facilitate balanced comparisons,
- Verifying data via extension records to reduce misreporting,
- Standardizing income per ha to account for land size heterogeneity.

Nevertheless, the possibility remains that the quota sample may overrepresent more accessible or cooperative farmers, or underrepresent remote or atypical cases. Future research should aim to employ stratified random sampling when full farmer lists become available to increase external validity.

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Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability: The datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement: This study was conducted in compliance with established ethical guidelines for social and economic research. Data were obtained through voluntary surveys and interviews with rice farmers after informed consent was obtained. Participants were fully informed about the objectives of the study and the intended use of the data. The anonymity and confidentiality of all respondents were rigorously protected. The study involved no interventions and posed no foreseeable risk to participants. All data were used exclusively for scholarly and academic purposes.

Author's Contribution: Rahmaddiansyah designed the study, conducted the survey, and performed the statistical analysis. Agussabti, Sabaruddin, and Agus Arip Munawar supervised and coordinated the research. Rahmaddiansyah and Intan Ulfa prepared the manuscript draft, and all authors critically reviewed and approved the final version.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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