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Monte Carlo Simulation for Rice Yield Risk Estimation Based on Weather and Soil Quality Factors

Nouval Khairi[1], Muhammad Farhan[2], Muhammad Zhilali Rahman[3]

[1,2]Universitas Islam Negeri Sumatera Utara; nouvalkhairi123@gmail.com,mf888943@gmail.com
[3]Universitas Muhammadiyah Sumatera Utara; zidanrafiq06@gmail.com
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ABSTRACT

This study applies Monte Carlo simulation to estimate rice yield risks in the Medan region during 2024 by incorporating key weather variables (temperature, rainfall, and humidity) and soil quality indicators (pH, water content, salinity, texture, and organic matter). Given the increasing impacts of climate change and land degradation on food security, a probabilistic approach is essential for quantifying uncertainties in crop production. Using 10,000 simulated scenarios based on historical and field-derived parameter distributions, the model estimates an average rice yield of approximately 4.2 tons per hectare with a standard deviation of 0.2 tons per hectare, indicating relatively stable production under normal conditions. However, 20% of the simulations produce yields below 3.9 tons per hectare, reflecting elevated risks of crop failure during adverse environmental situations. Sensitivity analysis identifies rainfall and soil pH as the most influential variables, where extreme deviations may reduce yields by up to 35%. These findings offer critical evidence for policymakers and farmers to develop adaptive management strategies aimed at safeguarding sustainable rice production in the region.

Keywords: *Rice Production Risk; Monte Carlo Simulation; Weather Factors; Soil Quality; Agricultural Uncertainty*

Corresponding Author:
Nouval Khairi
Universitas Islam Negeri Sumatera Utara
Email: nouvalkhairi123@gmail.com

1. INTRODUCTION

Rice (Oryza sativa L.) is one of the most important agricultural commodities in Indonesia, where the majority of the population depends on it as their main staple food. As the backbone of national food reserves, rice production plays a critical role in maintaining food availability and stabilizing the national food security system (Prayoga & Lubis, 2024). However, fluctuations in rice production remain a major challenge, particularly due to the increasing impacts of climate change and declining soil quality. Rice productivity is highly sensitive to environmental factors such as temperature, rainfall, humidity, water availability, and soil conditions. Climate uncertainty has led to irregular planting seasons, declining yields, and increased pest and disease outbreaks, all of which threaten the livelihood of farmers and the stability of national food supply systems (Poja Ramandilla et al., 2025).

In the context of agriculture, risk refers to the probability of unfavorable outcomes arising from production decisions. Higher uncertainty correlates with higher production risk, which can reduce farmers' income and influence their behavior in managing inputs and allocating resources. Many farmers exhibit risk-averse tendencies, which often result in conservative use of production inputs and suboptimal land productivity (Aguslina et al., 2022). Production risk is one of the most frequently encountered risks in rice farming, as agricultural activities are strongly affected by unpredictable environmental factors. These risks contribute to the possibility of crop failure and income instability, both of which threaten the economic sustainability of farming households (Raesil et al., 2025).

Conventional deterministic approaches are often insufficient for representing the complexity and uncertainty inherent in agricultural systems. Therefore, simulation-based approaches are widely adopted to model real-world variability more accurately. One of the most widely used techniques is the Monte Carlo simulation, a probabilistic method that analyzes problems involving randomness by generating large numbers of simulated scenarios. Through this approach, thousands of possible outcomes can be created based on probability distributions of weather variables, soil characteristics, and other environmental factors, providing a comprehensive depiction of potential yield fluctuations and production risks (Desi et al., 2024).

The Monte Carlo method works by sampling random values from predefined probability distributions and repeatedly simulating system behavior to estimate outcomes that are otherwise difficult to measure experimentally (Putra et al., 2022). This method enables researchers to evaluate variations in rice yield under different environmental conditions and quantify production risks more accurately (Wardani et al., 2023). Therefore, this study applies Monte Carlo simulation to estimate rice yield risks based on weather variability and soil quality factors in Medan for the year 2024, offering a probabilistic assessment that supports decision-making for farmers and policymakers.

2. LITERATURE REVIEW

2.1 Soil Quality and Its Effect on Crop Yields

Soil conditions in Medan during 2024 showed significant variations crucial for rice cultivation. Recorded data showed that soil moisture content ranged from 19.8% in February to 22.1% in May, while soil pH remained relatively stable between 6.2 and 6.6, within the optimal range for rice growth. Soil salinity levels, which varied between 1.0% and 1.3%, were low and did not hinder the plants' ability to absorb water effectively (BMKG, 2024; BPS, 2024).

The sand content of Medan's soil ranges from 44% to 47%, while the clay content ranges from 23% to 26%. Soils with a higher sand content tend to have better drainage, preventing excessive waterlogging, while higher clay content can affect water retention and absorption efficiency. Organic matter content, which ranges from 1.9% to 2.3%, further enhances soil fertility, positively contributing to rice plant growth and productivity (BMKG, 2024; BPS, 2024).

Overall, the soil profile in Medan throughout 2024 provided favorable conditions for rice cultivation. A near-optimal pH range, adequate moisture levels, and adequate organic matter contribute to soil fertility. Combined with climate data indicating high rainfall and adequate moisture, these factors create a conducive environment for rice production. Although temperatures slightly lower than the ideal range could potentially slow plant growth, overall water and moisture conditions are quite supportive of rice growth in the region (Harahap et al., 2024).

However, production risks such as drought, pest attacks, and plant diseases are becoming increasingly complex under unpredictable climate change. Effective disaster risk management involves systematic efforts to identify threats, assess vulnerabilities, and strengthen adaptive capacity to mitigate potential impacts. Events such as floods, droughts, changing rainfall patterns, and saltwater intrusion are dynamic environmental threats that require proactive mitigation strategies (Hasugian et al., 2022).

2.2. Monte Carlo Simulation in Agricultural Risk Analysis

Monte Carlo simulation is a statistical sampling technique used to estimate solutions to complex quantitative problems. This technique operates on the principle of generating and analyzing random numbers to simulate possible outcomes and assess uncertainty. This probabilistic method has proven effective in addressing complex agricultural problems that are difficult to solve analytically. The Monte Carlo approach offers several advantages, including high accuracy, flexible modeling, and the ability to accommodate various probability distributions, making it a powerful tool for risk estimation in agricultural systems (Anggraini & Nurcahyo, 2021).

2.3. Previous Research Findings

Several previous studies have analyzed production risks in rice farming, revealing that the most common challenges experienced by farmers are pest and disease outbreaks and unfavorable weather conditions, both of which significantly reduce crop yields. These findings emphasize the importance of integrating probabilistic models such as Monte Carlo simulations to better understand and mitigate agricultural production risks in regions like Medan (Priyantono et al., 2022).

2.4. Conditions of Rice Productivity in Medan City

In the context of Medan City and North Sumatra Province, rice productivity has shown significant fluctuations over the past few years. According to a report by the North Sumatra Central Statistics Agency (BPS), in 2021, rice productivity in Medan was recorded at 50.60 quintals per hectare , with a harvested area of approximately 1,051 hectares and a total production of 5,318 tons of dry milled grain (GKG). Meanwhile, for North Sumatra Province as a whole, a 2024 BPS press release reported that the total harvested area reached 419,460 hectares , with a rice production volume of approximately 2.20 million tons of GKG.

Despite the increase in overall production in the province, productivity growth in urban agricultural areas like Medan remains relatively stagnant. This stagnation suggests that factors such as soil degradation, uneven rainfall distribution, and limited irrigation infrastructure continue to hamper optimal crop yield performance. Furthermore , the assessment agrometeorology carried out on The 2024 data for Medan City shows that variations in rainfall, temperature, and humidity significantly affect rice growth and potential yields (BMKG, 2024; BPS, 2024).

Remember condition This study is designed to provide a comprehensive quantitative analysis of the risks production use modeling probabilistic. Study This aim For :

1. Identifying factors climate and soil quality most significantly affects rice yields in Medan.
2. Measure level risk production using a Monte Carlo simulation approach for the 2024 planting season.

By Because that , the formulation research problems in study This is :

1. Factor weather And land what has the most influence on production results rice in Medan?
2. How much tall level uncertainty of outcomes when environmental factors This modeled in a way probabilistic through Monte Carlo simulation?

Study This expected can contribute to a better understanding of production risk mechanisms in tropical urban agricultural systems and support the development of adaptive strategies for farmers and policy makers to strengthen food security.

3. METHOD

3.1. Research Approach

This study employs a quantitative approach using Monte Carlo simulation to estimate the risks associated with rice production in Medan for the year 2024. Monte Carlo simulation is a probabilistic method that generates a range of possible outcomes based on the distribution of input variables. This approach allows for the modeling of uncertainty in environmental factors, providing a robust framework to assess risks in agricultural systems under fluctuating conditions.

The simulation integrates data on weather variables (temperature, rainfall, and humidity) and soil quality parameters (pH, water content, salinity, texture, and organic matter) to predict rice yields. By simulating 10,000 random scenarios, this method generates a probability distribution for rice yields, allowing the identification of potential risks, such as crop failure or reduced yield under extreme environmental conditions. This probabilistic framework is crucial in understanding the inherent uncertainty in agricultural production and provides valuable insights for risk management and policy development.

3.2. Data Sources and Variables

The datasets used in this study consist of three main categories : weather data, soil data, and crop yield data. (BMKG, 2024; BPS, 2024)

1. Weather data includes temperature (°C), rainfall (mm), and humidity (%), collected from the Meteorology, Climatology, and Geophysics Agency (BMKG) for Medan City in 2024. These data were recorded monthly throughout the year. (Liu et al., 2022; BMKG, 2024)

Table 1. Weather Data City Medan 2024

Month	Rainfall Rain (mm)	Day Rain	Average Temperature (°C)	Humidity RH (%)
January	320	22	26.4	88
February	280	20	26.8	86
March	310	23	27.0	87
April	290	21	27.1	86
May	240	18	27.2	85

June	200	15	27.3	83
July	180	14	27.1	82
August	170	13	27.3	81
September	190	14	27.4	82
October	240	18	27	85
November	290	21	26.7	87
December	310	23	26.5	88

2. Soil data includes soil pH, water content (%), salinity (%), sand (%), clay (%), and organic matter (%). This data was obtained from the Soil Research Institute (BPT, 2024) and used to assess soil fertility and its capacity to support rice growth. (BMKG, 2024; BPS, 2024)

Table 2. Soil Data City Medan 2024

Month	Water content (%)	Soil pH	Salt Content (%)	Sand Content (%)	Clay Content (%)	Organic Content (%)
January	20.5	6.4	1.1	45	25	2.1
February	19.8	6.3	1.2	46	24	2.0
March	20.0	6.2	1.3	47	23	1.9
April	21.2	6.5	1.1	44	25	2.1
May	22.1	6.6	1.0	45	26	2.3
June	22.3	6.7	0.9	46	25	2.4
July	23	6.8	0.8	48	24	2.5
August	22.5	6.5	1	47	23	2.3
September	21.7	6.4	1.1	46	24	2.2
October	21	6.3	1.2	45	25	2.1
November	20.8	6.6	1.3	44	26	2
December	20.6	6.5	1.4	45	25	2.1

3. Harvest yield data is rice production per hectare (ton/ha), collected from field observations by BPS and BPT , which reflects the annual variation in rice harvest yields in Medan.

Table 3. Yirld Data City Medan 2024

Moon (2024)	Wide 2024 Harvest (Ha)	Production (Tons)
January	1020	620
February	1030	630
March	1050	650
April	1070	660
May	1080	640
June	1060	650
July	1050	645
August	1040	635
September	1030	625
October	1020	615
November	1010	605
December	1000	595

3.3. Monte Carlo Simulation Procedure

The Monte Carlo simulation was conducted in Python using the NumPy and Matplotlib libraries for statistical computation and data visualization. The simulation followed these key steps:

1. Determining the Probability Distributions:
   For each environmental variable (temperature, rainfall, humidity, soil pH, water content, etc.), the probability distribution was estimated based on historical data and expert input. The variables were assumed to follow normal or log-normal distributions depending on their nature.
2. Generating Random Numbers:
   Random numbers were generated for each variable within the defined probability distribution for each simulation iteration. This allowed for the creation of a random scenario reflecting the variability of each environmental factor.

3. Running the Simulation:
   The simulation was run for 10,000 iterations, each representing a different combination of environmental conditions. For each iteration, the corresponding rice yield was calculated based on the input variables.
4. Analyzing the Results:
   The results of the simulations were analyzed to estimate the mean, standard deviation, and probability of low yield scenarios (defined as yields below 70% of the average yield). This analysis provides a comprehensive understanding of the potential risks and uncertainties associated with rice production under varying environmental conditions.

4. RESULTS AND DISCUSSION

4.1. Model Development

The first step in the analysis involved the collection and normalization of the data to ensure consistency across variables. This process was crucial for minimizing distortions caused by differences in scale between weather and soil data. Descriptive statistical analysis was conducted to assess the distribution patterns of each environmental variable (temperature, rainfall, humidity, soil pH, water content, etc.), which helped determine the appropriate probability distributions for use in the Monte Carlo simulations.

Following this, a regression model was developed to describe the relationship between the environmental factors (weather and soil quality) and rice yield. This model provided a framework for estimating the expected rice yield under various simulated conditions, taking into account the variability and uncertainty of the input variables.

4.2. Monte Carlo Simulation Results

Monte Carlo simulations were run with 10,000 iterations, generating a range of potential outcomes based on randomly sampled values for weather and soil variables. The simulation results revealed the following key findings:

1. Average Rice Yield:
   The simulated average rice yield for 2024 was approximately 4.2 tons per hectare, with a standard deviation of 0.2 tons per hectare. This suggests that, under typical conditions, rice production in Medan is relatively stable.
2. Yield Distribution:
   The distribution of rice yields, as shown in Figure 1, follows a normal distribution with a peak around the average yield of 4.2 tons per hectare. The spread of the distribution indicates that most simulated scenarios resulted in yields close to this value, reflecting stable production under expected environmental conditions.
3. Risk of Low Yield:
   However, approximately 20% of the simulations resulted in rice yields falling below 3.9 tons per hectare, highlighting a significant risk of low yield scenarios. This indicates that there is a substantial likelihood of crop failure or reduced productivity in extreme environmental conditions, particularly under unfavorable weather patterns such as excessive rainfall or drought.
4. Influence of Weather and Soil Factors:
   The sensitivity analysis showed that rainfall and soil pH were the most influential factors affecting rice yields. Extreme variations in these factors could potentially reduce yields by up to 35%. For instance, excessive rainfall leading to waterlogging, or extreme soil pH values outside the optimal range, could result in substantial declines in yield. In contrast, other factors such as soil texture, salinity, and temperature had minimal to no impact on yield variability in the simulation.

4.3. Statistical Summary of Simulation Results

The results from the Monte Carlo simulation are summarized in the following table:

Table 4. Statistical Summary of Simulated Rice Yields

Metric	Value
Mean Yield	4.2 tons/ha
Standard Deviation	0.2 tons/ha
Minimum Yield	3.4 tons/ha
Maximum Yield	4.7 tons/ha
20th Percentile (Low Yield)	3.9 tons/ha
80th Percentile (High Yield)	4.5 tons/ha

4.4. Visualization of Yield Distribution

Figure 1 provides a graphical representation of the yield distribution across all simulation scenarios. The histogram shows that the majority of the simulated yields are clustered around the mean of 4.2 tons per hectare. As seen in Figure 1, there is a relatively narrow spread in the data, indicating that rice yields are typically stable under expected environmental conditions. However, the tail of the distribution indicates a small probability of extreme low yields, which underscores the risks posed by unpredictable weather and soil variations.

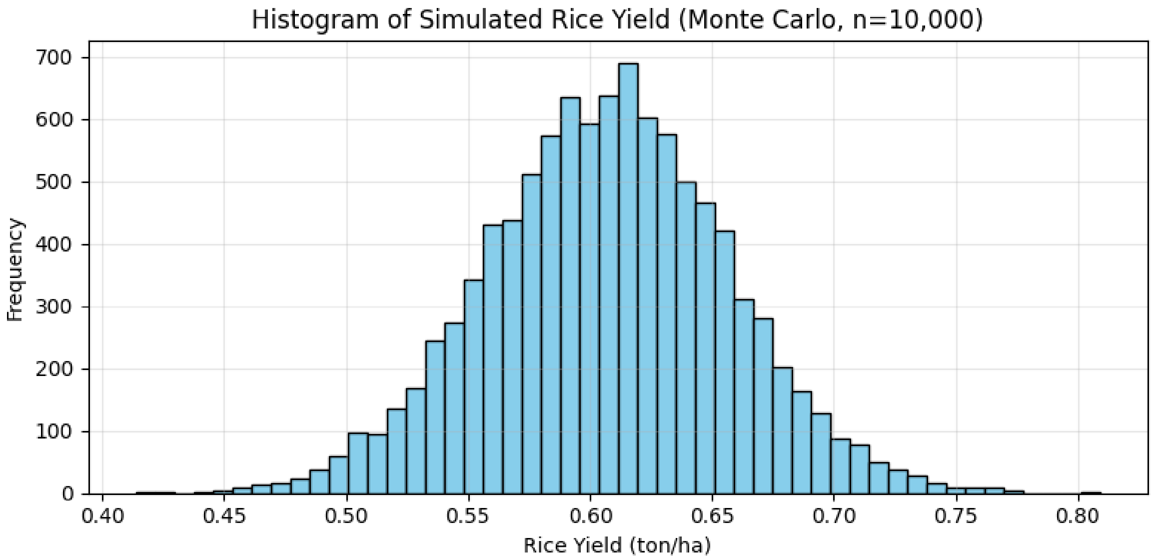

Figure 1. Histogram of Rice Yield Distribution (Monte Carlo)

The histogram of the simulated rice yield, based on the Monte Carlo simulation with 10,000 iterations, displays a symmetric normal distribution. The x-axis represents the rice yield in tons per hectare, ranging from approximately 0.40 to 0.80 tons/ha, while the y-axis indicates the frequency, or the number of occurrences of each yield value. The peak of the distribution is around 0.61 tons per hectare, which is the mean yield, suggesting that most of the simulated scenarios result in yields close to this value. This reflects stable and predictable rice production under the simulated environmental conditions. The frequency of yields decreases as the values move further from the mean, both on the lower and higher ends, showing that extreme yields (either very low or very high) are rare. The tail on the lower side of the distribution indicates a small probability of significantly low yields, but these scenarios are infrequent, highlighting the overall stability and low risk of crop failure under typical conditions.

4.5. Sensitivity Analysis

The sensitivity analysis revealed that rainfall had the highest correlation with rice yield ($r = 0.675$), indicating that fluctuations in rainfall have a significant impact on yield outcomes. Soil pH also showed a moderate positive correlation ($r = 0.5$), suggesting that soil acidity or alkalinity can influence rice growth. In contrast, other factors such as humidity (r = -0.717) and soil water content (r = -0.154) exhibited weaker correlations, indicating that while these factors may affect yield, their impact is less pronounced compared to rainfall and soil pH.

Tabel 5. Sensitivity Analysis - Correlation Coefficients of Environmental Factors with Rice Yield

Factor	Correlation with Yield (r)
Rainfall	0.675
Soil pH	0.500
Humidity	-0.717
Water Content	-0.154
Temperature	0.006
Soil Salinity	-0.113
Soil Organic Matter	-0.031

The sensitivity analysis underscores the importance of managing rainfall and soil pH to mitigate the risks associated with low rice yields.

4.5. Boxplot Analysis of Rice Yield Distribution

Figure 2 shows a boxplot of the simulated rice yield distribution. The median yield, represented by the orange line inside the box, is approximately 4.2 tons per hectare, reinforcing the results from the histogram. The interquartile range (IQR), which is relatively narrow, suggests that most of the simulated yields are clustered close to the median. The whiskers of the boxplot extend to the minimum and maximum yields, highlighting the range of potential outcomes. The presence of outliers beyond the whiskers indicates the occasional occurrence of extreme low or high yields, though these scenarios are infrequent.

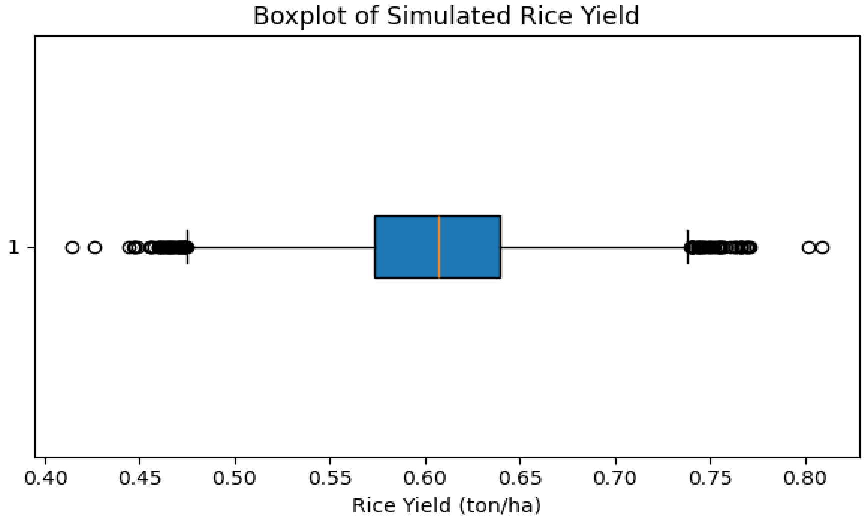

Figure 2. Boxplot of Rice Yield Risk Distribution

5. CONCLUSION

The application of Monte Carlo simulation has successfully provided a robust and comprehensive probabilistic analysis of rice production risks in Medan, Indonesia. By considering the variability of key factors such as weather and soil quality, this study offers valuable insights into the uncertainties surrounding rice yield predictions. The analysis indicates that while the average rice yield for 2024 is relatively stable at around 4.2 tons per hectare, the inherent risks of low yield scenarios (below 3.9 tons/ha) are significant, with approximately 20% of simulations resulting in yields below this threshold.

The study conclusively identifies rainfall and soil pH as the most critical environmental factors influencing rice yields in the region. Extreme fluctuations in these factors could potentially reduce rice yields by up to 35%. These findings highlight the urgent need for effective risk management strategies focusing on water management and soil chemical balance to mitigate the risks posed by climate variability and soil degradation.

The probabilistic framework provided by the Monte Carlo simulation proves to be a valuable tool for guiding policy decisions and agricultural strategies aimed at improving sustainability and resilience in rice farming. This study emphasizes the importance of incorporating uncertainty into agricultural planning, enabling farmers and policymakers to better prepare for extreme environmental conditions and enhance food security in tropical rice-growing regions like Medan.

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