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Rainfall Variability and Rice Production under Climate Change: Empirical Evidence and Climate-Smart Adaptation in Bogor Regency, Indonesia

Santosa Pradana Putra Setya Negara[1]✉, Rhavida Anniza Andyani[2], Ni Putu Vida Indriani[3], Akmil Asril[4], Lucas Nathaniel Tan[5], Lucas Adrian Lee[6], Somsak Phommasone[7]

[1,2]Faculty of Informatics, Technology, and Science, Universitas Muhammadiyah Madiun, Indonesia
[3,4]Faculty of Applied Science and Technology, Universitas Bali International Muhammadiyah, Indonesia
[5,6]School of Science and Technology, James Cook University, Singapore
[7]Faculty of Agriculture and Forest Resources, Souphanouvong University, Laos

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Abstract

Climate variability poses a growing challenge to rice production in Indonesia due to changes in rainfall patterns, water availability, and the increasing occurrence of extreme climatic events. This study aims to examine the relationship between rainfall variability and rice production and to identify climate-adaptation strategies for strengthening agricultural resilience. A qualitative approach combining a Systematic Literature Review (SLR), comparative analysis, and secondary-data analysis was employed. The literature review followed the PRISMA 2020 framework and synthesized 30 selected scientific studies, including three key studies used as principal synthesis sources. Secondary data on annual rainfall, ENSO conditions, harvested area, and rice production in Bogor Regency were analyzed for the 2018–2024 period. The findings indicate that El Niño-related rainfall deficits are associated with delayed planting, reduced water availability, and declining rice production, while excessive rainfall during La Niña periods may create risks associated with waterlogging, nutrient loss, pests, and diseases. In Bogor Regency, rice production declined from 385,400 tons in 2018 to 315,600 tons in 2023, coinciding with a reduction in annual rainfall to 2,550 mm during a moderate-to-strong El Niño phase. However, the seven-year dataset indicates temporal association rather than definitive causality. The study concludes that agricultural resilience requires climate-smart strategies integrating climate information, hydrological monitoring, adaptive planting calendars, efficient irrigation, climate-resilient varieties, integrated pest management, and digital decision-support systems. These measures can support sustainable rice production, farmer livelihoods, and food security amid increasing climate uncertainty.

Keywords: climate variability; water resource management; ENSO; rice farming systems; climate risk; agricultural vulnerability; food-system resilience; climate adaptation; hydrological variability

✉**Corresponding Author:**
Santosa Pradana Putra Setya Negara, Faculty of Informatics, Technology, and Science, Universitas Muhammadiyah Madiun, Indonesia
Email: spp760@ummad.ac.id

Introduction

Indonesia is an agrarian country in which rice remains a strategic commodity for national food security and rural livelihoods. The sustainability of rice production, however, is highly dependent on climatic conditions, particularly rainfall patterns, temperature, and water availability. Over the past decade, increasing climate variability has emerged as a major challenge to agricultural production. Climate change is no longer solely an environmental concern but has increasingly become an economic and livelihood issue for farmers across Indonesia [1]. One of the most influential climate-related phenomena is the El Niño-Southern Oscillation (ENSO), which can substantially alter seasonal rainfall patterns. During intensified El Niño events, many regions of Indonesia experience significant rainfall deficits, resulting in shifts in agricultural calendars and disruptions to conventional planting schedules [2].

Changes in rainfall patterns have direct implications for rice cultivation. Prolonged dry periods can delay planting, reduce irrigation water availability, and increase the risk of crop failure, particularly in areas that depend heavily on rainfall or surface water resources [3]. At the same time, increasing temperatures associated with climate change can accelerate evapotranspiration and reduce water-use efficiency, thereby affecting crop growth and productivity. Irregular rainfall may also create favorable conditions for agricultural pests and diseases, including brown planthopper infestations and rice blast [4]. Consequently, climate variability can generate fluctuations in agricultural productivity and increase uncertainty in farmers' production decisions. These effects extend beyond individual farms, potentially affecting rural livelihoods, agricultural supply, and national food security.

The impacts of climate variability are also evident in the socioeconomic conditions of farming communities. Climate uncertainty may increase psychological stress and anxiety among farmers because of the risks of crop failure, indebtedness, and loss of income. From an economic perspective, irregular rainfall can increase production costs as farmers may need to purchase or rent water pumps during droughts and apply additional pesticides when pest and disease pressures increase. Habib-ur-Rahman et al [5] reported that the El Niño phenomenon has a significant negative effect on the income of wet-rice farmers and may reduce their willingness to continue rice farming in the future. Farmers who remain highly dependent on conventional planting patterns are particularly vulnerable when the rainy season is delayed or the dry season becomes longer than expected [6]. Reduced harvests may subsequently affect not only farm-level income but also the stability of food prices and regional food availability. These interconnected impacts demonstrate the need for effective climate adaptation involving farmers, government institutions, researchers, and other stakeholders.

The vulnerability of agricultural systems is strongly influenced by geographical characteristics and the availability of local water resources. Observations conducted by the authors in the foothill area of Mount Salak, particularly in Pamijahan, Bogor Regency, indicate that many rice fields continue to utilize river flows originating from the mountainous region as their primary irrigation source. This water-resource configuration provides an important foundation for sustaining local agricultural activities. However, during prolonged dry seasons, declining river discharge can create competition for irrigation water and require farmers to distribute available water more efficiently. The authors' direct familiarity with agricultural land in the area further illustrates the importance of reliable water resources in maintaining rice production under changing climatic conditions.

The relationship between geographical conditions, water availability, and agricultural productivity has also been recognized in previous research. Regions with relatively abundant water resources tend to possess greater capacity to withstand rainfall variability than areas that depend predominantly on direct precipitation [7]. Therefore, strengthening agricultural resilience requires an integrated adaptation strategy that combines improved irrigation management, climate information, drought-tolerant rice varieties, and technology-based agricultural monitoring. Climate information systems and satellite-based monitoring, for example, can support the identification of rainfall anomalies and provide information that may assist farmers in adjusting planting schedules and managing water resources more effectively [8].

Several previous studies have established the relationship between climate variability, rainfall patterns, and agricultural production in Indonesia. Wang et al [9] demonstrated that climate variability associated with El Niño can delay the monsoon and consequently postpone planting seasons and reduce agricultural yields. Baffour-Ata [10] further reported that extreme rainfall variability can contribute to crop failure through drought and flooding, highlighting the importance of adjusting agricultural calendars to changing climatic conditions. Similarly, Garbanzo et al [11] examined the implications of changes in extreme rainfall frequency for irrigation water availability and farmers' planting patterns. Collectively, these studies demonstrate that changes in rainfall regimes can generate cascading effects on agricultural systems. Nevertheless, their analytical approaches differ, ranging from climate modeling and agricultural calendar development to analyses of agricultural and water-resource dynamics.

Despite these contributions, an important research gap remains. Much of the existing literature relies on historical datasets or macro-scale climate modeling and therefore may not adequately capture recent extreme weather dynamics, particularly developments after 2018. In addition, empirical studies that integrate recent rainfall trends with agricultural production and local water-resource conditions in mountainous or foothill regions remain relatively limited. This limitation is particularly relevant for Bogor Regency, where agricultural activities in the Mount Salak foothill region are closely connected to mountainous water resources and local hydrological conditions.

Accordingly, this study investigates changes in rainfall patterns and their implications for agricultural production, irrigation water availability, and the vulnerability of food crops in Indonesia, with particular attention to Bogor Regency as a representation of the Mount Salak foothill region. The study combines a Systematic Literature Review (SLR) to synthesize existing evidence with secondary-data analysis of annual rainfall trends and rice production during the 2018–2024 period. This approach enables the study to contextualize recent empirical changes within the broader body of climate–agriculture research while examining the relationship between rainfall variability and regional rice production. The novelty of the study therefore lies in integrating recent empirical rainfall and rice-production data with the findings of previous studies to provide a more current assessment of agricultural vulnerability to climate variability at the regional level.

This research is particularly important because Indonesia's agricultural sector remains highly dependent on climatic and hydrological conditions. Changes in rainfall patterns can disrupt planting schedules, reduce irrigation reliability, increase production risks, and ultimately threaten food security [12]. By identifying the relationship between rainfall anomalies and fluctuations in rice production, this study is expected to provide empirical evidence that can support the development of more responsive agricultural adaptation strategies. The findings may contribute to improved irrigation and water-resource management, climate-informed agricultural planning, and policy formulation aimed at strengthening the resilience and sustainability of rice production under increasing climate uncertainty.

Method

This study employed a qualitative descriptive research approach combined with a systematic literature review (SLR), comparative analysis, and secondary-data analysis. The qualitative approach was used to systematically identify, interpret, and synthesize scientific evidence concerning the relationship between climate variability, rainfall patterns, and rice production in Indonesia. A qualitative descriptive approach enables phenomena to be systematically described based on information obtained from various relevant sources (Moleong, 2010).

The research was conducted in two complementary stages. The first stage consisted of a systematic literature review to identify and synthesize previous empirical findings concerning climate change, rainfall variability, irrigation water availability, and agricultural productivity. The second stage involved the analysis of secondary climatological and agricultural data from Bogor Regency for the 2018–2024 period. The integration of these two stages was intended to connect findings from the existing scientific literature with recent empirical evidence from an agricultural region located in the foothills of Mount Salak.

The literature review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework to improve the transparency and reproducibility of the identification, screening, eligibility assessment, and inclusion of relevant studies [13]. The overall literature-selection process is presented in Figure 1.

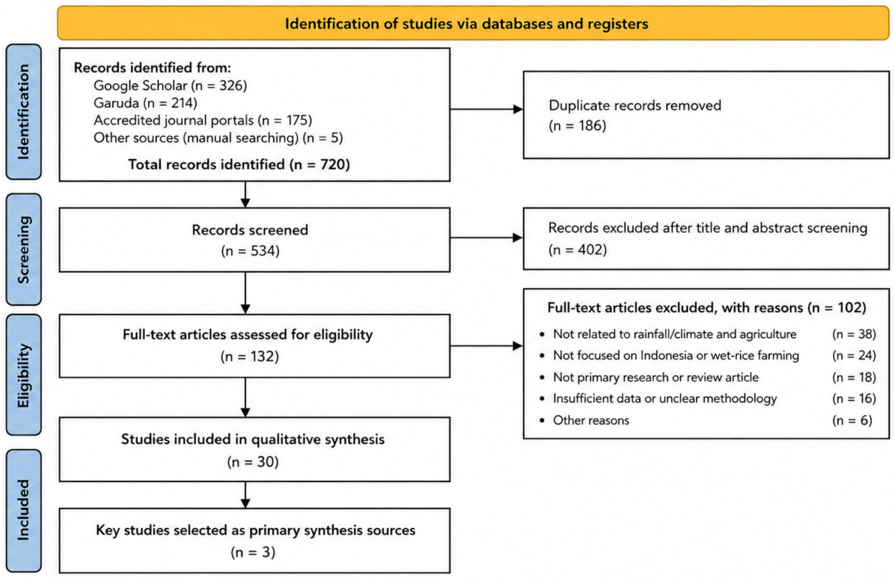


Figure 1. PRISMA 2020 Flow Diagram of the Literature Identification, Screening, Eligibility Assessment, and Inclusion Process

a. Data Sources

The study utilized two main categories of data: scientific literature and secondary empirical data. The scientific literature comprised published studies addressing climate change, rainfall variability, ENSO, agricultural productivity, irrigation water availability, and the vulnerability of rice production to climatic conditions.

A total of 30 scientific studies that met the established selection criteria were included in the qualitative synthesis. Among these studies, three key journal articles were subsequently identified as the principal synthesis sources because of their strong relevance to the relationship between climate variability, rainfall patterns, and agricultural production. The remaining studies provided complementary evidence and contextual support for the synthesis.

The empirical component utilized secondary data on rainfall and rice production in Bogor Regency during the 2018–2024 period. Agricultural data included harvested area and total rice production. Agricultural statistics were obtained from the Central Bureau of Statistics (*Badan Pusat Statistik*/BPS), while climatological information was obtained from the relevant climatological station and associated climate records. Climate reports and satellite-based observations were also considered where relevant to support the interpretation of rainfall variability.

b. Literature Search Strategy

The literature search was conducted systematically through Google Scholar, Garuda, and accredited journal portals. The search strategy employed combinations of keywords related to the principal research variables and geographical context. The main keywords included *climate change*, *rainfall variability*, *rainfall patterns*, *El Niño*, *rice production*, *agricultural productivity*, *irrigation*, *food security*, and *Indonesia*. Boolean operators such as AND and OR were used where appropriate to combine related keywords and broaden or narrow the search results.

All identified records were compiled and screened according to predefined eligibility criteria. Duplicate records were removed before title and abstract screening. The remaining records were assessed for their relevance to climate variability, rainfall patterns, and agricultural production. Articles considered potentially relevant were subsequently subjected to full-text assessment.

The literature-selection procedure followed the PRISMA 2020 framework, which provides a structured approach for transparently reporting the identification, screening, eligibility, and inclusion of studies in systematic reviews [14]. The complete selection process is presented in Figure 1.

c. Eligibility Criteria and Study Selection

To ensure consistency and relevance in the literature selection process, predefined inclusion and exclusion criteria were established before the screening stage. These criteria were applied to the identified records during title and abstract screening and subsequently during full-text assessment.

The selection process consisted of four stages: identification, screening, eligibility assessment, and inclusion. During the identification stage, records were collected from the selected databases and other relevant sources. During screening, duplicate records were removed and titles and abstracts were assessed. Potentially relevant publications were then evaluated through full-text assessment based on the criteria presented in Table 1. Studies satisfying the eligibility requirements were subsequently included in the qualitative synthesis.

A total of 30 studies were included in the final qualitative synthesis. Three studies with particularly strong relevance to climate change, rainfall variability, and agricultural production were selected as the principal synthesis sources. The complete selection process and the number of records retained or excluded at each stage are illustrated in Figure 1.

d. Secondary Data Collection

Secondary empirical data were collected to examine recent patterns of rainfall and rice production in Bogor Regency. The study area was selected because Bogor Regency encompasses agricultural areas surrounding the foothills of Mount Salak, where rice cultivation is influenced by local hydrological conditions and the availability of water from mountainous and riverine systems.

The observation period covered 2018–2024, allowing the study to examine recent variations in climatic and agricultural conditions. The principal agricultural indicators were harvested area and total rice production, while rainfall data were organized according to the corresponding annual observation period. The datasets were arranged chronologically to facilitate comparison between rainfall patterns and rice-production dynamics.

The empirical data were subsequently examined alongside the findings synthesized from the selected literature. This integration was intended to determine whether the regional patterns observed in Bogor Regency were consistent with the broader climate–agriculture relationships reported in previous studies.

e. Data Analysis

The analysis consisted of three complementary procedures: qualitative thematic synthesis, comparative analysis, and descriptive analysis of secondary empirical data.

First, the selected scientific literature was analyzed using the Miles and Huberman framework, which comprises data reduction, data display, and conclusion drawing. During data reduction, relevant information from each study was extracted and categorized according to the principal themes of the research, including rainfall variability, climate anomalies, ENSO, irrigation water availability, rice productivity, agricultural vulnerability, and farmer adaptation [15].

During the data-display stage, the extracted information was systematically organized to facilitate comparison among the selected studies. The comparison focused on similarities and differences in research objectives, geographical contexts, data sources, analytical approaches, and major findings. Particular attention was given to evidence concerning the effects of rainfall deficits, excessive rainfall, temperature changes, and climate anomalies on rice production and irrigation availability.

Second, comparative analysis was conducted to identify recurring patterns and contrasting findings across the reviewed literature. The comparative results were synthesized narratively to establish the broader relationship between climate variability and agricultural production in Indonesia. This process also facilitated the identification of limitations and unresolved issues in previous studies.

Third, the secondary data from Bogor Regency were analyzed descriptively. Annual rainfall patterns were compared with changes in harvested area and total rice production during 2018–2024. The analysis focused on identifying temporal trends, increases or decreases, and potential correspondence between rainfall variability and fluctuations in rice production. The empirical findings were then interpreted in relation to the evidence obtained from the systematic literature review.

The integration of literature findings and secondary empirical data was used to develop an evidence-based interpretation of agricultural vulnerability to climate variability. The analysis did not assume a direct causal relationship between rainfall and rice production solely from descriptive trends. Instead, it focused on identifying temporal associations and contextual patterns that could provide empirical evidence for understanding how changing rainfall conditions may influence agricultural production and water-resource availability.

f. Research Procedure

The overall research procedure consisted of six sequential stages. First, the research problem and analytical scope were defined based on the relationship between climate variability, rainfall patterns, and rice production. Second, relevant scientific literature was identified through systematic searches of the selected databases. Third, duplicate records were removed and the remaining studies were screened according to their titles and abstracts. Fourth, potentially relevant studies were assessed through full-text examination based on the eligibility criteria presented in Table 1. Fifth, the final literature set was analyzed and synthesized using qualitative and comparative approaches. Sixth, the literature findings were integrated with secondary rainfall and rice-production data from Bogor Regency for 2018–2024.

Table 1. Eligibility Criteria for the Systematic Literature Review

Criterion	Inclusion Criteria	Exclusion Criteria
Research topic	Studies addressing climate change, climate variability, rainfall patterns, rainfall anomalies, or related climatic phenomena	Studies unrelated to climate variability or rainfall
Agricultural focus	Studies examining rice production, agricultural productivity, irrigation, water availability, crop vulnerability, or agricultural adaptation	Studies with no substantive connection to agricultural production
Geographical relevance	Studies focusing on Indonesia or providing evidence relevant to tropical agricultural systems and the Indonesian context	Studies whose geographical or climatic context has no meaningful relevance to the research objectives
Research variables	Studies examining relationships between climatic conditions and agricultural or water-resource outcomes	Studies that do not address the relationship between climate and agricultural or water-resource conditions
Publication type	Peer-reviewed scientific journal articles and scientifically credible research publications with clearly reported methods and findings	Editorials, opinion articles, news articles, non-scientific documents, and publications without sufficient methodological information
Methodological quality	Studies with clearly described research objectives, data sources, analytical procedures, and findings	Studies with unclear methodology, insufficient data, or findings that cannot be evaluated
Relevance to research objectives	Studies that provide evidence supporting the analysis of climate variability and its implications for rice production	Studies that do not substantially contribute to the research questions
Publication period	Recent studies were prioritized, while influential earlier studies were retained when they provided important foundational evidence	Publications with outdated or insufficiently relevant information that did not contribute to the research synthesis

The research procedure provided an integrated analytical framework combining evidence from previous scientific research with recent regional empirical data. This framework was used to assess patterns in rainfall variability and rice production while providing contextual evidence for understanding agricultural vulnerability and its implications for irrigation management, climate adaptation, and regional food security.

Result and Discussion

The results of the systematic literature review and the analysis of secondary data from Bogor Regency for the 2018–2024 period provide evidence of the close relationship between climate variability, rainfall dynamics, water availability, and rice production. The findings indicate that changes in rainfall patterns associated with ENSO phenomena can influence irrigation water availability and planting seasons, which subsequently affect rice growth, productivity, and the broader agricultural system. These impacts extend beyond crop production to include changes in pest and disease dynamics, farmer livelihoods, and food security. At the same time, the findings highlight the importance of strengthening climate adaptation through the integration of climate information, water-resource management, agricultural technology, and farmer-level decision-making. Accordingly, the results and discussion are organized into four main themes: (1) rainfall variability, ENSO dynamics, and water availability; (2) climate variability and rice production, including physiological mechanisms and empirical evidence from Bogor Regency; (3) climate-induced agroecosystem risks, food security, and socioeconomic implications; and (4) climate-smart agriculture and adaptive strategies for resilient rice production.

a. Rainfall Variability, ENSO Dynamics, and Water Availability in Rice-Growing Areas

The results indicate that rainfall variability is one of the most important climatic factors influencing the stability of rice-based agricultural systems in Indonesia. Changes in rainfall patterns are particularly important in regions where agricultural activities remain highly dependent on seasonal rainfall and surface-water resources. Previous studies have shown that climate variability in Indonesia is characterized not only by changes in annual rainfall totals but also by shifts in the timing, intensity, and duration of rainfall events [16]. Such changes can create uncertainty in the beginning and end of the rainy and dry seasons, making conventional planting calendars increasingly less reliable. Recent observations based on Global Satellite Mapping of Precipitation (GSMaP) data further indicate that rainfall intensity and duration have become increasingly dynamic, highlighting the importance of satellite-based information for improving rainfall monitoring and agricultural decision-making [17].

The influence of ENSO on rainfall variability provides an important explanation for these changes. El Niño generally reduces rainfall over much of Indonesia, whereas La Niña tends to increase rainfall. However, the agricultural consequences of these phenomena depend not only on the amount of rainfall received but also on its temporal distribution. A relatively high annual rainfall total does not necessarily indicate adequate water availability throughout the rice-growing cycle if rainfall is concentrated within a short period. Conversely, a moderate annual rainfall deficit can become agriculturally critical when it occurs during land preparation, planting, tillering, flowering, or grain-filling stages. Therefore, rainfall variability should be interpreted from both a quantitative and temporal perspective.

The relationship between ENSO intensity, rainfall deficit, planting delay, and production loss is summarized in Table 2.

Table 2. Estimated Impact of ENSO Intensity on Rice Production

Climate Condition	Rainfall Deficit (%)	Planting Delay (days)	Estimated Production Loss (million tons)	Agricultural Risk
Normal	0	0	0.00	Low
Weak El Niño	10.05	10	0.25	Moderate water stress
Moderate El Niño	25.00.00	20	0.54	High water stress
Strong El Niño	>40	>30	1.12	Severe drought and crop-failure risk

Table 2 demonstrates a consistent escalation of agricultural risk as rainfall deficits increase. Under normal conditions, the absence of a rainfall deficit corresponds to no estimated planting delay and no estimated production loss, providing a baseline against which anomalous climatic conditions can be interpreted. Under weak El Niño conditions, a 10.5% rainfall deficit is associated with an estimated 10-day planting delay and a production loss of approximately 0.25 million tons. The estimated impact becomes substantially greater under moderate El Niño, where a 25% rainfall deficit is associated with a 20-day delay and an estimated production loss of 0.54 million tons. Under strong El Niño conditions, rainfall deficits exceeding 40% and planting delays exceeding 30 days are associated with an estimated production loss of 1.12 million tons [18]. These figures illustrate the potential nonlinear escalation of agricultural risk as climatic anomalies intensify. Importantly, these values represent estimates reported in the cited source rather than direct estimates generated from the present Bogor dataset. They therefore serve as a comparative benchmark for interpreting the regional empirical evidence presented in the subsequent sections.

The implications of rainfall variability become particularly relevant in the foothill region of Mount Salak, Bogor Regency, including Pamijahan. The geographical characteristics of this region provide relatively favorable water conditions because rice fields are supported by river flows and other water sources originating from the mountainous area. The orographic effect associated with mountainous topography also contributes to relatively high rainfall conditions [19]. Nevertheless, the presence of relatively abundant water resources does not eliminate the vulnerability of agricultural systems to climate variability. During periods of prolonged rainfall deficits, river discharge can decrease, while during periods of excessive rainfall, high runoff and increased river discharge may create flooding and waterlogging risks. Thus, water availability should not be interpreted simply as the presence or absence of water, but rather as the availability of water in the appropriate quantity and at the appropriate time.

The conceptual relationship between ENSO, rainfall variability, hydrological conditions, and agricultural activities is illustrated in Figure 2.

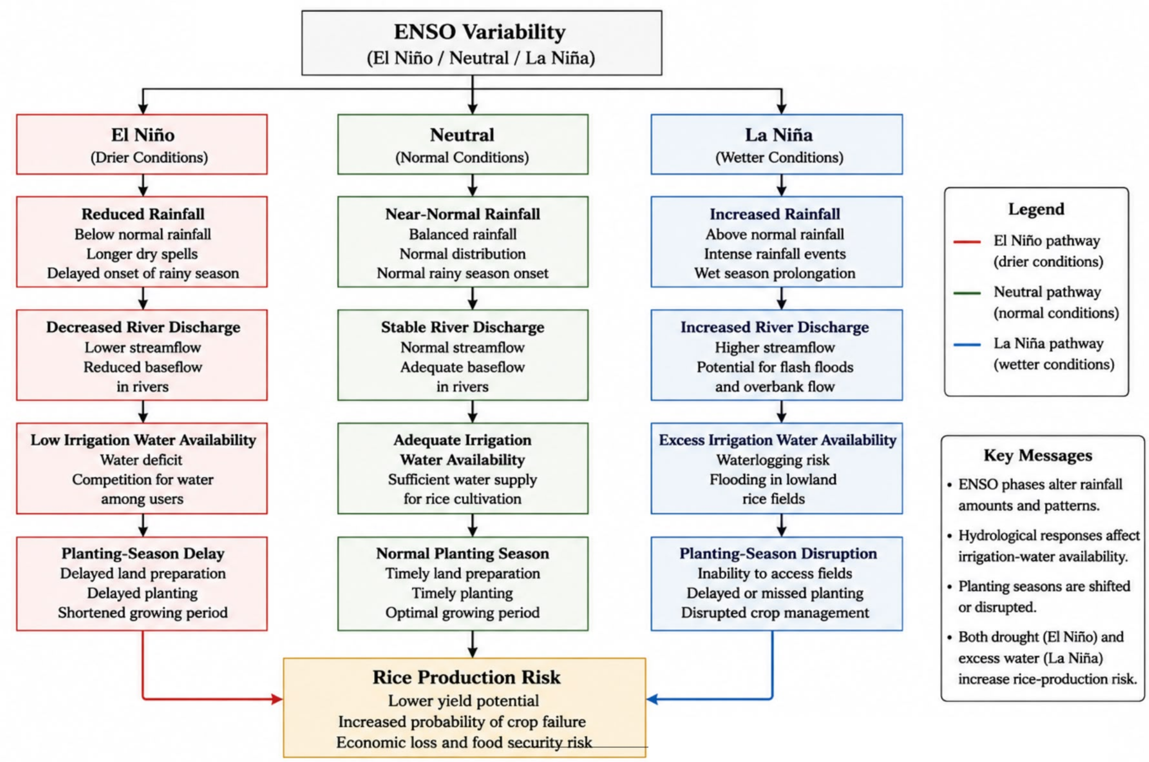


Figure 2. Conceptual Pathway Linking ENSO Variability, Rainfall Anomalies, River Discharge, Irrigation-Water Availability, Planting-Season Shifts, And Rice-Production Risk In The Mount Salak Foothill Region

Figure 2 emphasizes that the effect of ENSO on rice production is mediated through several interconnected hydrological and agricultural processes. During El Niño, reduced rainfall can lower river discharge and groundwater recharge, thereby increasing competition for irrigation water. Farmers may consequently need to modify irrigation schedules, delay planting, or reduce the cultivated area when water availability becomes insufficient [20]. In contrast, La Niña can increase rainfall and river discharge, but excessive rainfall may produce a different set of agricultural risks, including flooding, waterlogging, nutrient loss, and increased disease pressure. Therefore, the relationship between rainfall and agricultural productivity should not be conceptualized as a simple linear relationship in which more rainfall always produces higher yields. Instead, rice production depends on maintaining an appropriate balance between water availability, crop requirements, soil conditions, and the timing of rainfall events [21].

This distinction is particularly important for farmers in the Mount Salak foothill region because the agricultural system benefits from mountainous water resources but remains exposed to variations in the broader regional climate system. During a prolonged dry season, reduced river discharge requires farmers to distribute irrigation water more efficiently among agricultural plots [22]. Conversely, during periods of intense rainfall, the same river systems may experience increased discharge and runoff, potentially causing inundation in low-lying agricultural areas. Consequently, adaptation strategies need to address both water scarcity and excess-water conditions rather than focusing exclusively on drought management.

A comparative visualization of the three principal climatic conditions relevant to rice cultivation is presented in Figure 3.

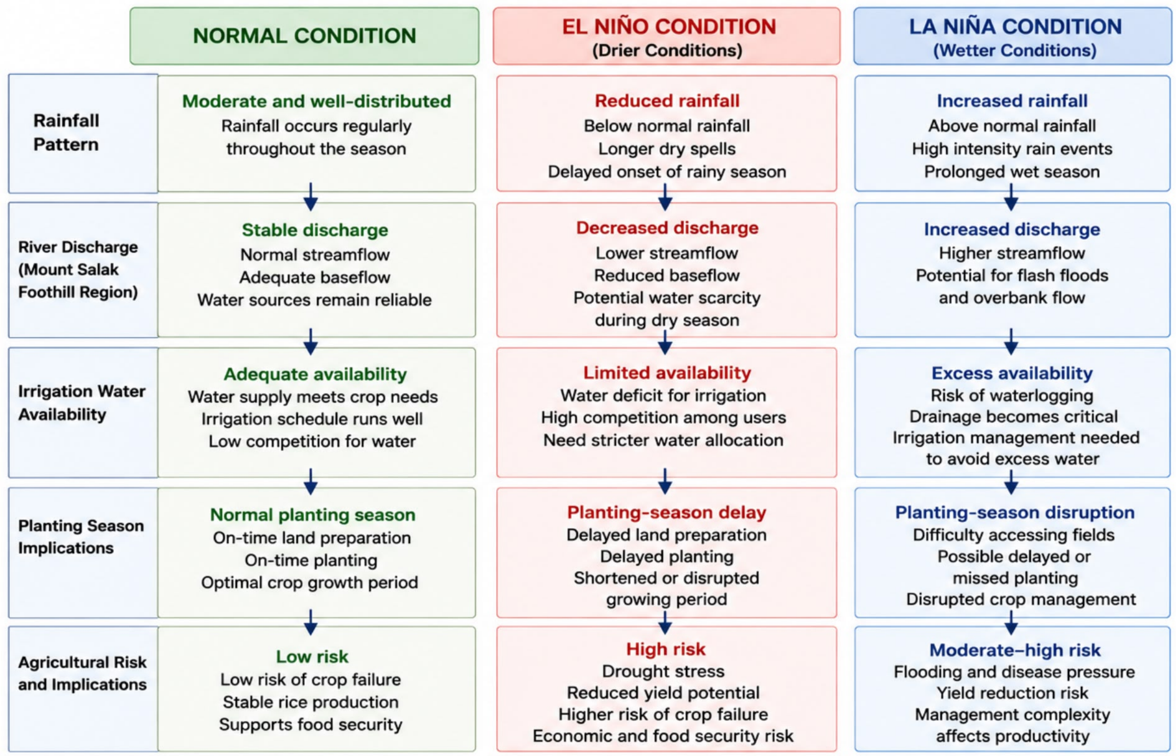


Figure 3. Comparative Illustration of Rainfall Conditions, River Discharge, Irrigation Availability, and Agricultural Risks Under Normal, El Niño, and La Niña Conditions

Figure 3 highlights the asymmetric nature of climate-related agricultural risks. Under normal conditions, relatively balanced rainfall and river discharge provide a more stable basis for irrigation and planting activities. Under El Niño conditions, declining rainfall and river discharge can generate water deficits, resulting in delayed planting and increased crop-failure risks [23]. Under La Niña conditions, increased rainfall may improve water availability but can simultaneously increase the risk of flooding, prolonged inundation, nutrient leaching, and disease development. This comparison is important because it demonstrates that agricultural resilience cannot be achieved simply by increasing water availability. Instead, effective management requires the capacity to respond to both deficits and excesses in water supply. In this context, real-time climate monitoring and hydrological information can support farmers in determining when to plant, how much water should be allocated, and when drainage measures are required [24].

Another important finding concerns the increasing uncertainty of the onset of the rainy season. Farmers may experience a *false start* when rainfall occurs at the beginning of what appears to be the rainy season, encouraging planting activities, but is subsequently followed by an extended dry period [25]. Such conditions can be particularly damaging because the crop has already been established and requires continuous water availability. A false start therefore represents not merely a delay in planting but a potential mismatch between crop development and climatic conditions. This mismatch can increase the probability of replanting, additional input costs, and reduced yields. In mountain-slope areas, changes in rainfall timing can also increase the risk of floods and landslides during high-intensity rainfall events, further complicating agricultural and water-resource management [26].

The findings also suggest that traditional agricultural knowledge based primarily on historical seasonal patterns may become less reliable under increasingly variable climatic conditions. Farmers traditionally use accumulated experience to determine planting periods, irrigation practices, and crop management. However, when the timing and intensity of rainfall become less predictable, historical experience alone may not adequately capture current climatic conditions. This does not imply that local knowledge should be abandoned; rather, it should be complemented with scientifically generated climate information. Satellite observations, weather forecasts, rainfall monitoring, and hydrological data can provide additional information that allows farmers to make more timely decisions. Chaudhry et al [27] demonstrate the potential of satellite-based rainfall observations to characterize dynamic changes in rainfall intensity and duration, supporting the development of more responsive climate-monitoring systems.

Overall, the results demonstrate that rainfall variability and ENSO dynamics influence agricultural water availability through interconnected atmospheric, hydrological, and management processes. The Mount Salak foothill region illustrates an important paradox: despite possessing relatively favorable mountainous water resources, rice production remains vulnerable to climate variability because the timing, intensity, and distribution of water are as important as the total amount of water available. El Niño increases the risk of water deficits, delayed planting, and reduced production, whereas La Niña can create risks associated with excessive rainfall and waterlogging [28]. These findings support the need to strengthen climate-informed agricultural management through improved rainfall monitoring, early warning systems, adaptive planting calendars, and more efficient irrigation management. Such measures are particularly important for regions where agricultural livelihoods remain strongly dependent on climatic and hydrological conditions [29].

b. Climate Variability and Rice Production: Physiological Mechanisms and Empirical Evidence from Bogor Regency

Climate variability affects rice production through a combination of hydrological, physiological, and agroecological mechanisms. Rice requires adequate water availability throughout its growth cycle, particularly during critical stages such as tillering, flowering, and grain filling [10]. When water availability becomes insufficient during these stages, photosynthetic activity and biomass accumulation can be reduced, ultimately affecting the number of productive tillers, grain filling, and grain weight [30]. Conversely, excessive water availability can also disrupt plant growth through prolonged inundation, reduced oxygen availability in the root zone, nutrient leaching, and increased susceptibility to pests and diseases. Therefore, the relationship between climate variability and rice production is not simply determined by the total amount of annual rainfall but also by its timing, intensity, and distribution throughout the growing season.

In the Mount Salak foothill region, these mechanisms are particularly relevant because rice cultivation depends on a combination of rainfall and surface-water resources. During periods of rainfall deficit, declining river discharge can reduce irrigation availability and increase competition for water among agricultural users [31]. The resulting soil-moisture deficit may affect plant physiological processes, particularly when water stress occurs during reproductive development. Zurek et al [32] reported that environmental stress during critical growth stages can reduce productive tillers, increase the proportion of unfilled grains, and decrease grain weight. These physiological responses provide an important explanation for why reductions in water availability can ultimately translate into lower rice productivity.

Changes in soil moisture can also affect nutrient dynamics. Repeated transitions between excessively wet and relatively dry conditions may disrupt soil microbial activity and the decomposition of organic matter, potentially reducing nutrient availability for plant uptake [33]. At the same time, excessive rainfall can increase nutrient leaching, whereas prolonged drought can restrict nutrient movement through the soil profile. These processes may further constrain vegetative and reproductive growth. In addition, climatic disturbances can modify the balance of rice-field ecosystems. Changes in temperature, humidity, and water conditions may alter pest and pathogen development, while potentially reducing the effectiveness of natural enemies [34]. Consequently, climate-related production losses should be understood as the outcome of interconnected physiological and ecological processes rather than as a single direct response to rainfall changes.

The empirical data for Bogor Regency during 2018–2024 provide further evidence of substantial fluctuations in rice production under different climatic conditions. Table 3 summarizes annual rainfall, ENSO conditions, harvested area, and rice production during the observation period.

Table 3. Annual Rainfall, ENSO Conditions, Harvested Area, and Rice Production in Bogor Regency, 2018-2024

Year	Annual Rainfall (mm)	ENSO Status	Harvested Area (ha)	Rice Production (tons)	Production Change from 2018 (%)
2018	3,850	Normal	62,150	385,400	0.00
2019	2,900	Weak El Niño	58,300	340,200	−11.73
2020	4,100	La Niña	60,500	375,100	−2.67
2021	4,350	La Niña	61,200	380,500	−1.27
2022	4,200	La Niña	61,00	378,000	−1.92
2023	2,550	Moderate–Strong El Niño	54,800	315,600	−18.11
2024	2,800	Transition/Neutral	56,100	328,400	−14.79

Source: Compiled from the secondary rainfall, climatological, and agricultural data used in this study.

Table 3 reveals a notable temporal correspondence between rainfall variability and fluctuations in rice production. The baseline year, 2018, recorded annual rainfall of 3,850 mm under normal climate conditions, accompanied by the largest harvested area in the observed period (62,150 ha) and the highest rice production (385,400 tons). In 2019, annual rainfall decreased to 2,900 mm during a weak El Niño phase. Simultaneously, the harvested area declined to 58,300 ha and rice production decreased to 340,200 tons, representing an 11.73% reduction relative to 2018. This simultaneous decline suggests that rainfall conditions may influence production not only through yield formation but also through farmers' capacity to maintain cultivated and harvested areas.

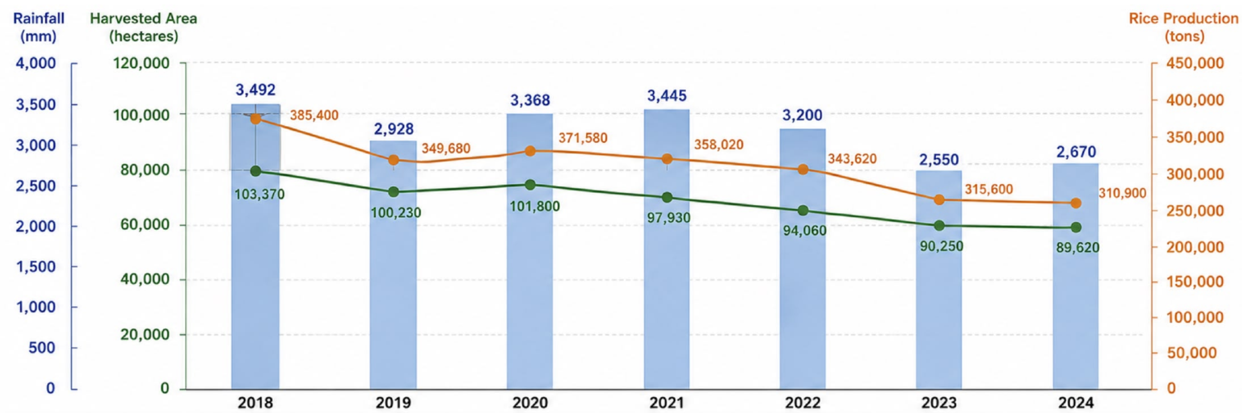
The rainfall and rice-production trend over the observation period can be visualized through the following illustration.

Figure 4. Annual rainfall trend in Bogor Regency, 2018–2024, showing temporal fluctuations associated with ENSO conditions

Figure 4 is expected to demonstrate substantial interannual variability rather than a uniform increase or decrease in rainfall. Rainfall declined from 3,850 mm in 2018 to 2,900 mm in 2019 and subsequently increased to more than 4,000 mm during 2020–2022, when La Niña conditions prevailed. The highest annual rainfall in the dataset occurred in 2021 at 4,350 mm. Rainfall then decreased sharply to 2,550 mm in 2023 during the moderate-to-strong El Niño phase before increasing modestly to 2,800 mm in 2024. This temporal pattern supports the broader literature indicating that ENSO contributes substantially to interannual rainfall variability in Indonesia [35]. However, the pattern also demonstrates that annual rainfall totals alone cannot fully explain agricultural performance because the timing and distribution of rainfall within the agricultural calendar remain important.

The strongest decline in production occurred in 2023. Annual rainfall decreased to 2,550 mm, the lowest value recorded during 2018–2024, while the harvested area decreased to 54,800 ha and rice production fell to 315,600 tons. Compared with 2018, production declined by approximately 18.11%. The magnitude of this decline is consistent with the broader evidence that stronger El Niño conditions can produce substantial rainfall deficits, delay planting, and increase water stress in agricultural systems [36]. The decline in harvested area is also important because it suggests that climatic stress may influence production through two interconnected pathways: reduced productivity per unit area and reduced capacity to maintain the cultivated area.

The relationship between annual rainfall and rice production is further examined through the following illustration.



	2018	2019	2020	2021	2022	2023	2024
Rainfall (mm)	3,492	2,928	3,368	3,445	3,200	2,550	2,670
Harvested Area (hectares)	103,370	100,230	101,800	97,930	94,060	90,250	89,620
Rice Production (tons)	385,400	349,680	371,580	358,020	343,620	315,600	310,900
ENSO Phase	La Niña (Weak)	El Niño (Weak)	La Niña (Strong)	La Niña (Moderate)	La Niña (Weak)	El Niño (Moderate–Strong)	El Niño (Weak–Moderate)

Figure 5. Bogor Regency Climate and Agriculture Trends (2018-2024): Annual Rainfall, ENSO Phase, Harvested Area, and Rice Production

Figure 5 provides a visual comparison between rainfall levels and rice production for each year of the observation period. The data suggest that relatively dry years, particularly 2019 and 2023, coincided with lower rice production, whereas the wetter La Niña years of 2020–2022 were associated with production levels that were closer to the 2018 baseline. However, the relationship is not perfectly linear. For example, the highest rainfall recorded in 2021 (4,350 mm) did not produce the highest rice output, which remained slightly below the 2018 level. This finding indicates that excessive rainfall does not necessarily translate into higher production. High rainfall may generate waterlogging, reduce soil aeration, increase nutrient losses, and create favorable conditions for disease development [37]. Therefore, the empirical evidence supports the interpretation that rice productivity is associated with an optimal range and distribution of water availability rather than simply with increasing rainfall.

The physiological mechanism underlying these observations can be summarized as a sequence beginning with climatic stress and progressing toward disruption of yield formation. Under rainfall deficits, insufficient soil moisture can restrict photosynthesis and nutrient uptake, reduce tillering, and interfere with flowering and grain filling [38]. Under excessive rainfall, prolonged inundation can impair root function and create environmental conditions conducive to pathogens. Such disturbances can further reduce photosynthetic efficiency and reproductive success. Helldén et al [39] similarly emphasized that climatic variability can modify agroecosystem conditions and increase pressure from pests and diseases. Consequently, both drought and excessive rainfall can reduce the stability of rice production, although through different physiological and ecological pathways.

The 2020–2022 period provides an important contrast. During these years, rainfall remained above 4,000 mm and rice production ranged from 375,100 to 380,500 tons. Although these production levels were relatively high compared with the El Niño years, they did not exceed the 2018 baseline of 385,400 tons. This observation suggests that increased rainfall under La Niña conditions may improve water availability but does not automatically increase production. Instead, excessive rainfall may introduce additional production constraints, including waterlogging, nutrient losses, and greater disease pressure [40]. Thus, the empirical evidence reinforces the argument that water adequacy and water timing are more important than rainfall volume alone.

Overall, the results demonstrate that climate variability affects rice production through multiple interconnected mechanisms. The empirical data from Bogor Regency indicate that periods of reduced rainfall, particularly during El Niño conditions, are associated with reductions in harvested area and rice production, while periods of excessive rainfall do not necessarily result in higher production [41]. The most substantial decline occurred in 2023, when moderate-to-strong El Niño conditions coincided with the lowest rainfall and production values in the observation period. These findings are consistent with the physiological mechanisms described in previous studies, particularly regarding water stress, disrupted grain formation, and changes in agroecosystem conditions [42]. Nevertheless, because the empirical dataset contains only seven annual observations, the observed relationship should be interpreted as a temporal association rather than definitive evidence of causality. Further statistical analysis using longer time-series data would be necessary to quantify the strength and significance of the relationship between rainfall variability and rice production.

c. Climate-Induced Agroecosystem Risks, Food Security, and Socioeconomic Implications

The effects of climate variability on rice production extend beyond changes in rainfall, irrigation availability, and crop productivity. Changes in climatic conditions can modify the entire rice-field agroecosystem, including soil moisture, nutrient dynamics, pest and pathogen populations, and interactions between crops and natural enemies. These ecological changes subsequently generate socioeconomic consequences through reduced production, higher production costs, unstable farmer income, and potential fluctuations in food prices [43]. Therefore, climate change should be understood as a multidimensional risk that operates across agricultural, ecological, and socioeconomic systems rather than solely as a problem of water availability.

One of the most important agroecosystem consequences of rainfall variability is the alteration of field-level microclimatic conditions. Rainfall deficits can produce soil-moisture stress, whereas excessive rainfall can cause prolonged inundation, nutrient leaching, and reduced oxygen availability in the root zone [44]. Both conditions can weaken rice plants and increase their vulnerability to environmental stress. In addition, changes in humidity, temperature, and water conditions can influence the development and population dynamics of plant-disturbing organisms. Fujimori et al [45] emphasized that climate variability can influence pest dynamics by modifying environmental conditions in agricultural ecosystems. Similarly, Balasundram et al [46] reported that rainfall, humidity, and the number of rainy days are among the climatic factors associated with brown planthopper populations.

The relationship between climatic disturbances and agroecosystem responses is summarized in Table 4.

Table 4. Cascading Impacts of Climate Variability on Rice Agroecosystems and Food Security

Climate-Related Change	Agroecosystem Response	Agricultural Impact	Socioeconomic Consequence
Rainfall deficit	Reduced soil moisture and water stress	Reduced crop growth and yield potential	Lower farmer income
Excessive rainfall	Waterlogging and nutrient leaching	Root stress and crop damage	Increased production costs
Increased humidity	Favorable conditions for pests and pathogens	Pest and disease outbreaks	Higher pesticide and management costs
Delayed rainy season	Disruption of planting schedule	Reduced or delayed harvested area	Income uncertainty
Prolonged dry season	Reduced irrigation availability	Increased crop-failure risk	Production and livelihood instability
Extreme rainfall events	Flooding and physical crop damage	Yield and field losses	Disruption of food supply
Recurrent climate anomalies	Agroecosystem instability	Production variability	Increased food-price and food-security risks

Table 4 demonstrates that climate variability produces a cascading sequence of impacts rather than an isolated effect on crop yield. Rainfall deficits primarily affect soil moisture and irrigation availability, while excessive rainfall creates different forms of stress, particularly waterlogging and nutrient loss. Both conditions can weaken plants and reduce their capacity to withstand pest and disease pressure. Increased humidity during wet periods may provide favorable conditions for pathogens and certain pests, while changes in the abundance and distribution of natural enemies can further disrupt ecological regulation [47]. Consequently, farmers may need to increase expenditures on irrigation, drainage, pesticides, or other crop-management inputs. These additional expenditures occur simultaneously with increased production uncertainty, creating a potentially significant economic burden for farming households.

Among the biological risks associated with rainfall variability, brown planthopper infestation is particularly relevant to rice production. Changes in rainfall and humidity can influence the reproduction and population dynamics of *Nilaparvata lugens*. Under favorable humid conditions, planthopper populations may increase rapidly and cause substantial damage to rice plants [48].

Similarly, rainfall and humidity conditions can influence the development of rice blast disease caused by *Magnaporthe oryzae*. High humidity and prolonged wet conditions can create favorable conditions for pathogen development, potentially reducing photosynthetic activity and interfering with grain formation. Liu et al [49] noted that climate change can alter the geographical distribution and development rates of pathogens and affect the effectiveness of natural biological control. These interactions demonstrate that climate variability may amplify agricultural risks through changes in the ecological balance of rice fields.

The sequence from climatic disturbance to agroecosystem damage and subsequent socioeconomic consequences can be represented as follows.

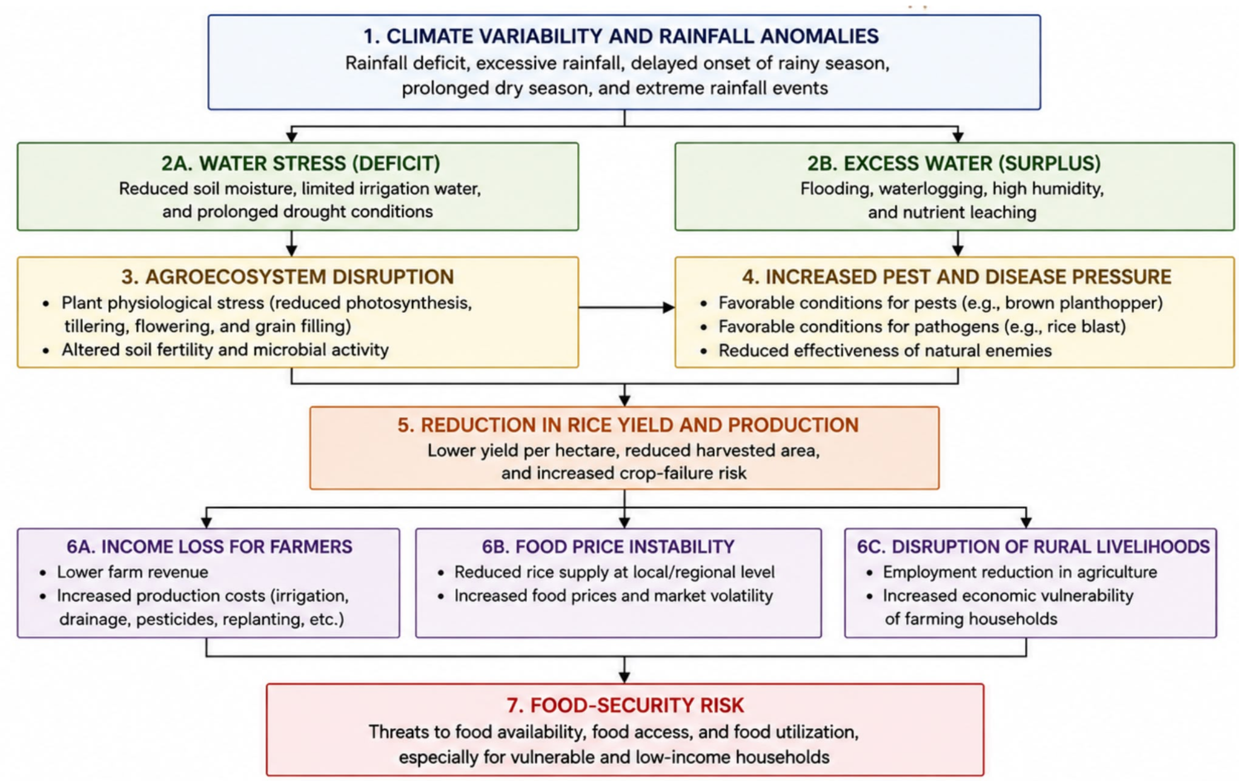


Figure 6. Flowchart Illustrating The Cascading Pathway From Climate Variability And Rainfall Anomalies To Water Stress Or Excess Water, Pest And Disease Pressure, Rice-Yield Reduction, Income Loss, Food-Price Instability, And Food-Security Risk

Figure 6 illustrates that climate-related risks propagate through multiple interconnected stages. The initial climatic disturbance may take the form of rainfall deficit or excessive rainfall. A rainfall deficit generates water stress, whereas excessive rainfall increases the probability of waterlogging and high humidity. These environmental conditions can subsequently influence plant physiological performance and the population dynamics of pests and pathogens [50]. The resulting reduction in crop health can contribute to lower yields and, when sufficiently severe, a decline in total agricultural production. At the household level, reduced production can lower farmers' revenues while simultaneously increasing expenditures for irrigation, drainage, pesticides, replanting, or other interventions [51]. At the regional and national levels, persistent production reductions may constrain food availability and contribute to food-price instability. The flowchart therefore demonstrates why climate change has implications beyond individual farms and should be considered a systemic food-security issue.

The socioeconomic implications become particularly important when production losses occur repeatedly. Farmers whose livelihoods depend predominantly on rice cultivation are exposed to both production risk and market risk. When climatic anomalies reduce harvest yields, farmers may experience lower revenues while still bearing relatively fixed production costs [52]. During droughts, additional costs may arise from purchasing or renting water pumps, while during periods of high pest and disease pressure, farmers may increase pesticide applications. Thus, the economic impact of climate variability may be substantially greater than the value of the immediate reduction in harvested production.

At the broader market level, reductions in rice production may contribute to supply constraints and upward pressure on food prices. Maja et al [53] reported that production declines associated with extreme weather can influence food prices because reduced supply affects market availability. Sharma et al [54] similarly highlight the economic implications of climate-related agricultural productivity changes, including their implications for regional economic performance and food security. Khanal [55] further emphasized that climatic variability can increase agricultural vulnerability through interacting effects on production and agroecosystem conditions. Therefore, the socioeconomic consequences of climate variability can extend from the individual farmer to the regional economy.

The relationship among climate variability, agricultural production, economic conditions, and food security can be synthesized in a broader conceptual framework.

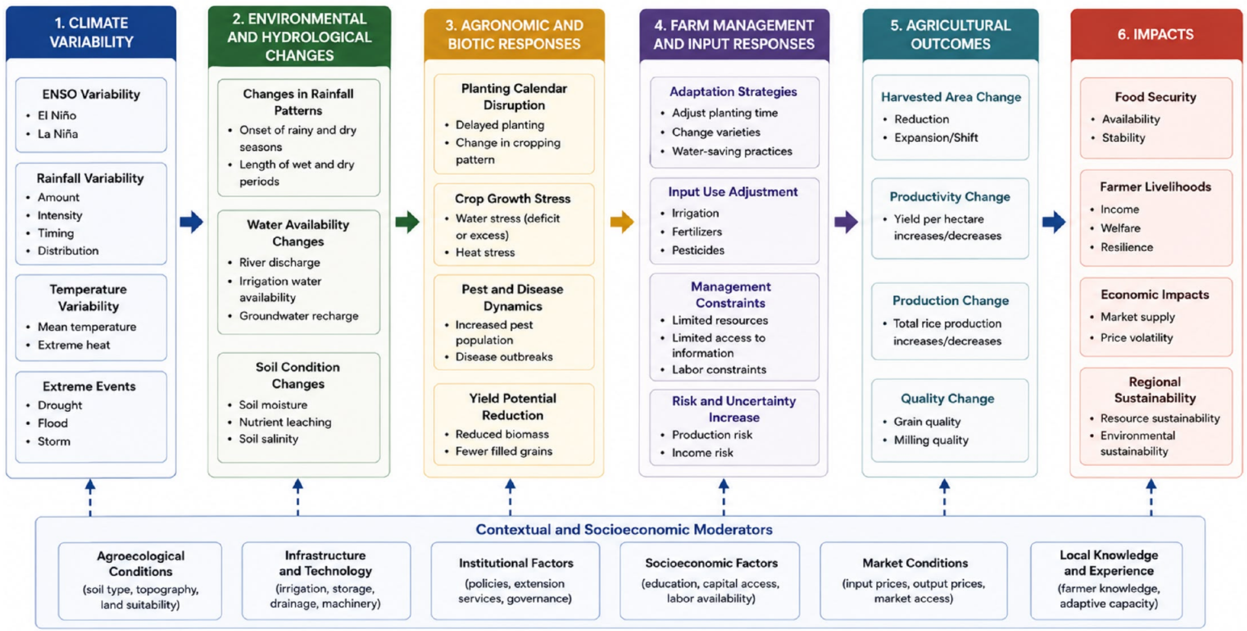


Figure 7. Casual Pathways Linking Climate Variability to Rice Production

Figure 7 emphasizes the multidimensional nature of climate-induced agricultural vulnerability. Climate variability represents the primary external pressure, manifested through rainfall anomalies, temperature changes, drought, flooding, and other extreme weather events. These pressures affect the agricultural production system through water availability, crop physiological stress, and pest and disease dynamics [56]. The resulting production instability influences farmer income and production costs and can subsequently affect regional food supply and market prices. At the food-security level, these processes influence not only food availability but also economic access to food and the stability of food supplies over time. This framework is particularly relevant to Indonesia because rice occupies a central position in the national food system. Bhatt et al [57] argue that climate change can amplify food insecurity, particularly in developing countries where agricultural production remains highly dependent on climatic conditions.

The implications for food security are further reinforced by the spatial variability of climate impacts. Atube et al [58] reported that extreme climate anomalies can have different spatial footprints across Indonesia, with some areas experiencing substantially longer drought periods during strong El Niño events. Consequently, national-level assessments of food security need to consider regional differences in climate exposure, agricultural characteristics, water-resource availability, and adaptive capacity. The Mount Salak foothill region illustrates this complexity. Although the region benefits from mountainous water resources, it is not immune to climate-induced risks because changes in rainfall timing and intensity can affect both water availability and agricultural operations [59]. Thus, local water-resource advantages can reduce vulnerability but cannot completely eliminate the effects of broader climate variability.

The interaction between rainfall variability and agroecosystem processes also has implications for soil fertility. Excessive rainfall may increase nutrient leaching, reducing the availability of essential nutrients to rice plants. Conversely, prolonged dry conditions can reduce soil moisture and microbial activity, potentially affecting organic-matter decomposition and nutrient cycling. These processes can weaken plant growth and make crops more susceptible to pest and disease attacks [60]. The resulting interaction creates a feedback mechanism in which climatic stress increases plant vulnerability, while ecological disturbances further increase the probability of production losses.

From a food-security perspective, the implications become more severe when production instability persists across multiple seasons or regions. Favier et al [61] reported that food-crop agriculture in Indonesia is highly vulnerable to climate change, with the potential risk of declining rice production averaging 1.37% per year. Although this estimate should not be directly applied to the Bogor Regency dataset without additional analysis, it provides broader evidence that climate-induced production losses can accumulate over time. Repeated production fluctuations can reduce the reliability of food supplies, increase market uncertainty, and place additional pressure on households with limited purchasing power.

The socioeconomic effects are therefore closely connected to the ecological effects of climate variability. A decline in production may reduce farmers' income, while increased expenditure for irrigation, pest control, or crop recovery further reduces household economic resilience. At the same time, consumers may face higher food prices when regional or national rice supplies decline. Low-income households are particularly vulnerable because food expenditure represents a relatively large proportion of their household budgets [62]. Consequently, climate adaptation in rice production should not be evaluated solely based on its ability to maintain yield but also on its capacity to protect farmer livelihoods and maintain affordable food supplies.

Overall, the findings demonstrate that climate variability generates cascading agroecosystem and socioeconomic risks. Rainfall deficits and excessive rainfall affect soil moisture, irrigation, plant physiology, pest and disease dynamics, and nutrient availability. These ecological effects can subsequently reduce rice productivity and increase production costs, leading to income instability among farmers. At a broader scale, persistent production fluctuations may affect food availability and price stability, thereby increasing food-security vulnerability [63]. The evidence therefore supports an integrated understanding of climate vulnerability in which agricultural adaptation must simultaneously address water management, crop health, pest and disease control, farmer livelihoods, and food-system resilience. This finding provides an important basis for the subsequent discussion of climate-smart agriculture and adaptive strategies as mechanisms for reducing the risks identified in this study.

d. Climate-Smart Agriculture and Adaptive Strategies for Resilient Rice Production

The findings presented in the previous sections demonstrate that climate variability affects rice production through interconnected changes in rainfall, water availability, crop physiology, agroecosystem conditions, and socioeconomic vulnerability. These impacts indicate that maintaining agricultural productivity under changing climatic conditions requires a transition from conventional, experience-based management toward a more adaptive and information-driven agricultural system. In this context, climate-smart agriculture (CSA) provides an appropriate framework because it emphasizes the improvement of agricultural productivity and resilience while promoting more efficient management of natural resources [64]. For rice-growing areas in the foothills of Mount Salak, climate-smart transformation is particularly relevant because farmers benefit from relatively abundant mountainous water resources but remain exposed to rainfall variability, seasonal uncertainty, drought, excessive rainfall, pests, and diseases.

One of the most important adaptation measures is the adjustment of planting schedules based on current climate and hydrological conditions. Farmers can no longer rely exclusively on traditional planting calendars when the onset and duration of rainy and dry seasons become increasingly uncertain. [39] emphasized the importance of adjusting planting times and using climate information to reduce the risk of crop failure under changing climatic conditions. Similarly, [65] highlighted the potential of climate information technology and planting calendars to support more accurate agricultural decision-making. Therefore, climate information should be transformed into practical recommendations that can be accessed and understood by farmers at the local level.

The principal climate-smart adaptation strategies identified from the literature and the findings of this study are summarized in Table 5.

Table 5. Climate-Smart Adaptation Strategies for Rice Production under Climate Variability

Climate Risk	Agricultural Impact	Adaptation Strategy	Supporting Technology/Approach	Expected Outcome
Rainfall deficit	Reduced soil moisture and irrigation availability	Efficient irrigation scheduling	Hydrological monitoring and water-level observation	Improved water-use efficiency
Delayed rainy season	Delayed planting and disrupted crop cycle	Climate-based planting calendar	Seasonal climate forecasting	Reduced planting failure
Strong El Niño	Drought stress and reduced crop growth	Drought-tolerant rice varieties	Improved seed technology	Reduced yield losses
Excessive rainfall	Flooding and waterlogging	Improved drainage and water regulation	GIS and hydrological mapping	Reduced crop damage
High humidity	Increased pest and disease pressure	Integrated pest management	Pest and disease early-warning system	Reduced crop losses
Rainfall uncertainty	Difficulty in farm-level decision-making	Real-time climate monitoring	Weather stations and satellite observations	More timely decisions
Production instability	Income and livelihood vulnerability	Crop diversification	Agricultural planning and extension services	Increased livelihood resilience
Uneven water distribution	Competition for irrigation water	Participatory water management	Farmer-group coordination and water monitoring	More equitable water allocation

Table 5 demonstrates that adaptation to climate change cannot be reduced to a single technological intervention. Different climate risks require different combinations of management strategies [66]. For example, drought conditions require more efficient irrigation and drought-tolerant varieties, whereas excessive rainfall requires drainage and water-level management. Similarly, pest and disease risks require an integrated pest-management approach rather than simply increasing pesticide applications. This distinction is particularly important because climate variability can generate opposing risks within the same agricultural system. The table also demonstrates the importance of combining technology with institutional mechanisms. Weather stations, satellite observations, GIS, and hydrological monitoring can provide valuable information, but their effectiveness depends on whether the information is translated into decisions that farmers can implement. Farmer groups and agricultural extension services therefore remain important components of climate-smart transformation. Crop diversification can further reduce dependence on a single commodity and increase livelihood resilience, consistent with [67].

The integration of climate information, technological resources, agricultural management, and institutional support can be represented through the following framework.

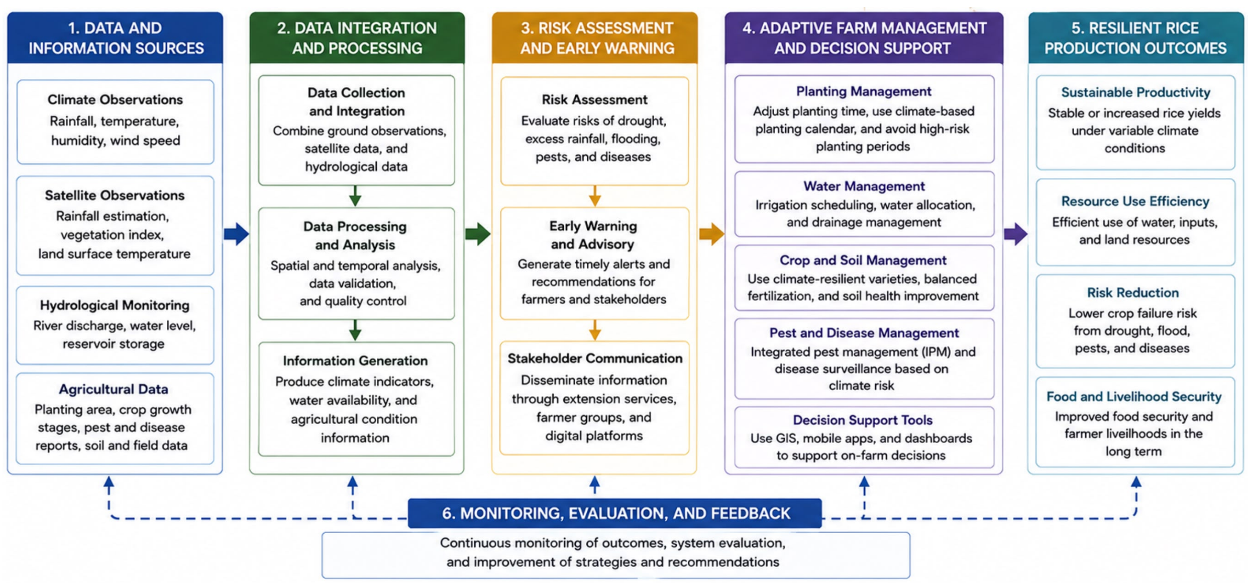


Figure 8. Climate-Smart Agriculture Framework Integrating Climate Information, Satellite And Hydrological Observations, Risk Assessment, Adaptive Farm Management, And Resilient Rice Production

Figure 8 illustrates that climate-smart agriculture should be implemented as an integrated decision-support system rather than as a collection of independent technologies. The process begins with the acquisition of climate information from weather observations, satellite-based rainfall monitoring, and hydrological measurements. These data are then transformed into an assessment of climate risks relevant to agricultural activities. The resulting information can support decisions concerning planting calendars, irrigation scheduling, crop selection, and pest and disease management. The framework therefore places information and decision-making at the center of agricultural adaptation. This approach is particularly relevant to the Mount Salak foothill region because the availability of river and mountain water resources can be managed more effectively when information about rainfall and hydrological conditions is available in a timely manner. Ngetich et al [68] demonstrated the usefulness of satellite-based rainfall observations for characterizing dynamic rainfall conditions, while Sandström et al [69] emphasized the importance of adaptive agricultural management in responding to climate-related risks.

The implementation of climate-smart agriculture also requires institutional transformation. Farmers cannot be expected to independently interpret complex climate forecasts, satellite observations, and hydrological information. Instead, information needs to be communicated through farmer groups, agricultural extension workers, local governments, and research institutions. Yagaso [70] emphasized the importance of collaboration among agricultural stakeholders in facilitating innovation adoption and strengthening farmers' capacity to respond to changing environmental conditions. In the Mount Salak foothill region, farmer groups can serve as an important intermediary for coordinating irrigation schedules, disseminating climate information, and implementing collective responses to drought or excessive rainfall.

The relationship between climate risks, adaptation measures, technological support, and expected outcomes is further detailed in Table 6.

Table 6. Implementation Priorities for Climate-Smart Rice Farming in the Mount Salak Foothill Region

Priority Area	Main Climate Problem	Recommended Intervention	Key Actors	Expected Resilience Outcome
Climate monitoring	Uncertain rainfall onset and duration	Continuous rainfall and weather monitoring	Climate agencies, researchers, local government	Improved anticipation of climate anomalies
Water management	Reduced river discharge during dry periods	Adaptive irrigation scheduling and water allocation	Farmers, farmer groups, irrigation managers	More efficient and equitable water use
Planting management	False starts and delayed rainy seasons	Dynamic planting calendar based on climate information	Farmers and extension workers	Reduced risk of planting failure
Crop management	Drought and excess-water stress	Use of drought- and flood-tolerant varieties	Farmers, seed providers, researchers	Greater crop tolerance to climatic stress
Pest and disease management	Increased pest/pathogen pressure	Climate-based integrated pest management	Farmers and extension workers	Reduced crop losses and pesticide dependence
Digital agriculture	Limited access to timely information	Mobile-based alerts, GIS, and remote sensing	Government, universities, technology providers	Faster and more precise decision-making
Institutional coordination	Fragmented climate and agricultural information	Farmer-group and stakeholder collaboration	Farmers, government, academics	Stronger collective adaptation capacity
Livelihood resilience	Production and income instability	Crop diversification and livelihood diversification	Farmers, extension agencies	Reduced dependence on rice production alone

Table 6 expands the adaptation framework by identifying the institutional and operational dimensions required for implementation. The table indicates that climate-smart transformation involves multiple actors and cannot be achieved solely through farmer-level interventions. Climate agencies and researchers are important for generating reliable climate information, while local governments and extension workers are responsible for translating such information into actionable recommendations [71]. Farmer groups can facilitate collective water management and the dissemination of agricultural innovations. Universities and technology providers can contribute through GIS, remote sensing, digital platforms, and decision-support systems. This multi-actor arrangement is particularly important because climate risks are not confined to individual agricultural plots. Drought, excessive rainfall, pest outbreaks, and irrigation shortages can affect multiple farmers simultaneously, making coordinated responses more efficient than isolated interventions. The framework also recognizes livelihood diversification as an important component of resilience because production shocks can directly affect household income.

At the farm level, adaptive irrigation management should become one of the central components of climate-smart agriculture in the Mount Salak foothill region. The existence of river flows originating from mountainous areas provides an important foundation, but water allocation must respond dynamically to changes in rainfall and discharge. During dry periods, farmers can prioritize irrigation during critical crop-growth stages and reduce unnecessary water use during periods when crop water requirements are relatively low. During periods of excessive rainfall, the emphasis should shift toward drainage and water-level regulation. Such an approach changes irrigation management from a relatively fixed practice into a dynamic system based on actual environmental conditions.

The use of drought- and flood-tolerant rice varieties is another important adaptation pathway. Climate variability creates different forms of stress, and varietal selection can reduce the sensitivity of rice crops to these stresses. However, improved varieties should not be regarded as a standalone solution. Their effectiveness depends on appropriate planting schedules, soil conditions, water management, and farmers' access to quality seed. Therefore, varietal adaptation should be integrated with climate information and agricultural extension services. Harrington et al [72] similarly identified the use of climate-adapted varieties as one of the strategies that can reduce production risks associated with changing climatic conditions.

Digital technologies offer additional opportunities to strengthen this adaptive capacity. Geographic Information Systems (GIS), remote sensing, satellite-based rainfall monitoring, and agricultural databases can be used to identify areas experiencing water stress, excessive rainfall, or production vulnerability. Satellite-based observations are particularly valuable in regions where ground-based monitoring networks are spatially limited. Baffour-Ata et al [10] demonstrated that GSMaP satellite data can capture rainfall characteristics that may not be fully represented by conventional observations. When integrated with local agricultural and hydrological data, such information can support more spatially targeted early-warning systems.

The practical implementation of these strategies in the study area can be summarized in the following framework.

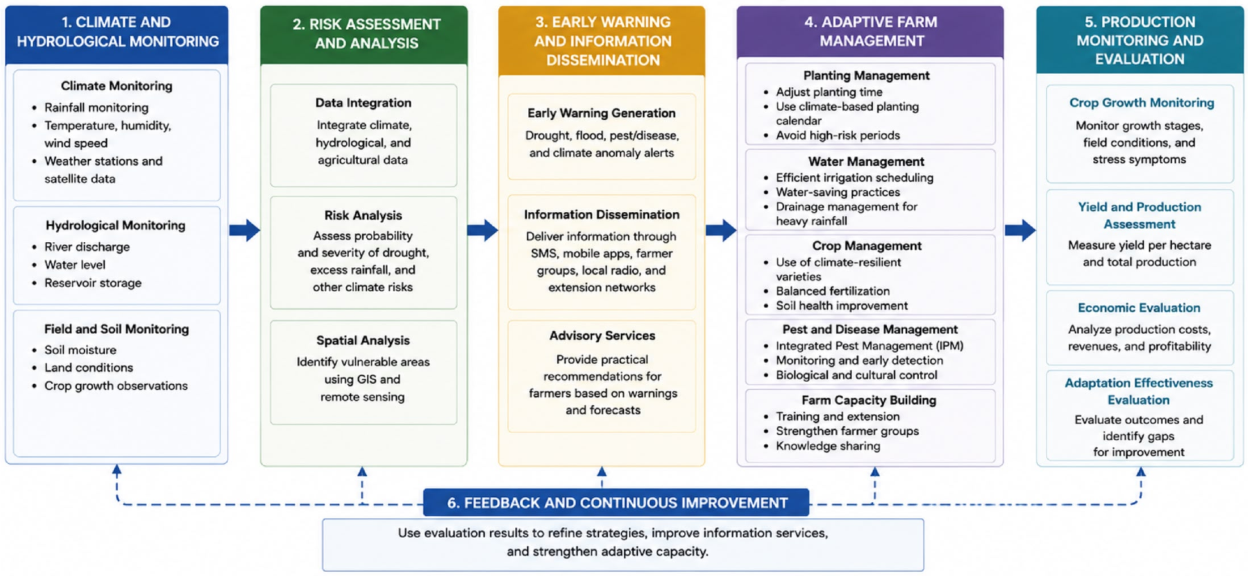


Figure 9. Implementation Framework For Climate-Smart Rice Farming In The Mount Salak Foothill Region, Integrating Climate Monitoring, Hydrological Assessment, Early Warning, Farmer Advisory Services, Adaptive Cultivation, And Production Evaluation.

Figure 9 emphasizes the importance of establishing a continuous feedback mechanism between environmental monitoring and agricultural decision-making. The process begins with climate and hydrological monitoring, followed by risk assessment and early-warning dissemination. Farmers then use the information to adjust planting schedules, irrigation, crop varieties, and pest-management practices [67]. The results of these interventions should subsequently be monitored and evaluated, creating feedback that can improve future agricultural decisions. This iterative approach is preferable to a one-directional adaptation model because climatic conditions vary between seasons and years. It also allows local experience to remain part of the decision-making process while being complemented by scientific information. In this sense, climate-smart agriculture does not replace farmers' knowledge but combines local knowledge with observational and technological evidence.

The findings also indicate that adaptation should be considered in terms of resilience rather than simply production maximization. Under increasingly uncertain climate conditions, the most appropriate agricultural strategy may not always be the one that produces the highest yield under optimal conditions, but rather one that minimizes losses under adverse conditions while maintaining acceptable productivity [73]. This perspective is particularly important for smallholder farmers whose economic capacity to absorb repeated production shocks is limited. Crop diversification, improved water management, adaptive varieties, and early-warning systems can therefore contribute not only to agricultural productivity but also to livelihood stability [74].

Overall, the results demonstrate that climate-smart agriculture provides a comprehensive pathway for strengthening the resilience of rice production in the Mount Salak foothill region. The required transformation involves the integration of climate information, hydrological monitoring, adaptive planting calendars, efficient irrigation, climate-resilient varieties, integrated pest management, digital technologies, and institutional collaboration. The approach should also incorporate farmer participation because adaptation measures are more likely to be effective when they reflect local environmental conditions and farmers' practical needs. Collaboration among farmers, extension workers, local governments, academics, and technology providers is therefore essential [75]. Ultimately, the objective of climate-smart transformation is not merely to maintain rice production under changing climatic conditions but to establish an agricultural system that is more anticipatory, resource-efficient, economically resilient, and capable of sustaining food security in the face of increasing climate uncertainty.

Conclusion

This study demonstrates that climate variability, particularly changes in rainfall patterns associated with El Niño and La Niña phenomena, represents an important challenge to the stability of rice production in Indonesia. The systematic literature review indicates that climate-related changes affect agricultural systems through interconnected mechanisms involving rainfall variability, irrigation-water availability, planting-season shifts, crop physiological stress, pest and disease dynamics, and socioeconomic vulnerability. The findings further demonstrate that agricultural vulnerability is determined not only by the amount of rainfall received but also by its timing, intensity, duration, and distribution throughout the crop-growth cycle.

The empirical analysis of Bogor Regency during 2018–2024 provides regional evidence consistent with these broader findings. Lower rainfall during El Niño conditions, particularly in 2019 and 2023, coincided with reductions in harvested area and rice production. The most pronounced decline occurred in 2023, when annual rainfall decreased to 2,550 mm and rice production declined to 315,600 tons, compared with 385,400 tons in the 2018 baseline year. Conversely, the relatively high rainfall observed during the La Niña period of 2020–2022 was associated with comparatively higher production levels, although production did not exceed the 2018 baseline. This finding indicates that excessive rainfall does not necessarily increase rice production and may instead introduce risks associated with waterlogging, nutrient loss, and increased pest and disease pressure. Given the limited number of annual observations, these patterns should be interpreted as temporal associations rather than definitive evidence of causality.

The study also highlights that the availability of mountainous water resources in the Mount Salak foothill region does not completely eliminate agricultural vulnerability to climate variability. Changes in rainfall can alter river discharge and irrigation availability, while shifts in the onset of rainy and dry seasons can disrupt conventional planting calendars. Consequently, farmers require more adaptive approaches that combine local knowledge with reliable climate and hydrological information.

Climate-smart agriculture offers an appropriate pathway through the integration of climate monitoring, satellite and hydrological observations, adaptive planting calendars, efficient irrigation management, climate-resilient rice varieties, integrated pest and disease management, and digital decision-support technologies.

Overall, the findings emphasize that strengthening rice-production resilience requires a systemic and climate-informed approach rather than isolated agricultural interventions. Collaboration among farmers, farmer groups, extension workers, government institutions, researchers, and technology providers is essential to translate climate information into timely and practical agricultural decisions. The proposed climate-smart framework provides a basis for improving water-use efficiency, reducing production risks, strengthening farmer livelihoods, and supporting food security under increasing climate uncertainty. Future research should extend the empirical time series, incorporate seasonal or monthly rainfall and production data, and apply statistical or econometric models to quantify the strength and significance of the relationships between climatic variables, water availability, and rice productivity. Such approaches would provide stronger causal evidence and further support the development of location-specific climate adaptation policies for Indonesia's rice-producing regions.

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