GeoScienceEd *7(3) (2026)*

Jurnal Pendidikan, Sains, Geologi, dan Geofisika

http://jpfis.unram.ac.id/index.php/GeoScienceEdu/index

Climate Change Implications for Indonesian Agriculture: A Systematic Literature Review

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DOI: https://doi.org/10.29303/goescienceed.v7i3.1585

Article Info:
Received : May, 20 2026
Revised : June, 06 2026
Accepted : June, 17 2026
Published : June, 27 2026

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Abstract: Climate change is becoming an increasing threat to the food security of Indonesia, as it affects agricultural systems, changes the rainfall, raises sea levels, and intensifies extreme weather events. Conducted in the PRISMA protocol, this Review synthesizes the empirical evidence provided by 32 peer-reviewed articles, screened out of a preliminary set of 320 articles, published in 2020-25 in Google Scholar, Sinta, and ScienceDirect and in DOAJ. It is demonstrated that even a 1-2degC rise in temperature can lead to a 25 percent drop in national output of rice, salt intrusion along the coastlines can lower it by approximately 30 percent. Even though farmers have been engaging in different local adaptation responses such as reworking the planting calendars, they are usually stifled by lack of access to climate information, financial support, and technology. Among the mitigation alternatives, the Alternate Wetting and Drying (AWD) technique, 4R nutrient management, and peatland rehabilitation can be singled out as one of the most promising solutions to this issue as they allow mitigating greenhouse gas emissions and enhancing the agroecosystem resilience at the same time. This review suggests the incorporation of holistic adaptation and mitigation policies in national policies, institutional capacity building, and faster breeding and spreading of stress-resistant Plant varieties that can endure climatic change.

Keywords: Climate Change; Rising Global Temperatures; Food Security; Indonesia's Agricultural Sector; Mitigation of Greenhouse Gas Emissions

Citation: Meilanie, T., Akhsan, H., & Kistiono. (2026). Climate Change Implications for Indonesian Agriculture: A Systematic Literature Review. *Jurnal Pendidikan, Sains, Geologi, Dan Geofisika (GeoScienceEd Journal)*, *7*(3), 2820–2832. https://doi.org/10.29303/goescienceed.v7i3.1585

Introduction

Climate change and global warming currently represent an existential threat to food system and food security in Indonesia since this archipelagic nation is very sensitive to climatic conditions, temperature rise, rainfall variation and rising sea level that lower productivity of agriculture, breakdown supply chains and exposes millions of smallholder farmers to threats of failure of crops and socio-economic exposure (Iklim et al., 2025). Global warming which increases the rate and magnitude of heat waves, extreme weather conditions and the changes in the monsoons directly affect the physiological stages of the plants including the flowering and seed filling stages, which further affect the yield and the quality of rice, corn and palm oil in different parts of Indonesia (Yuan et al., 2024). Moreover, there is a compounding effect between the threats of increasing temperatures and extreme events like severe droughts or flash floods, which intensifies the possibilities of compound events like droughts and heat waves that enhance the biomass degradation and lower agricultural productivity (Bolan et al., 2024).

Such effects are not merely biophysical, but they also initiate nutritional and health effects, including a decrease in the availability of local food and an elevated risk of malnutrition amongst the risk population. Climate change is thus a cross sectoral phenomenon, which needs a combined policy response (Colozza et al.,

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2025). On the local scale, the studies conducted in Indonesia demonstrate that variations in the rainfall regime and the rise in sea levels have also contributed to the salinization of coastal lands and the intrusion of salty water into alluvial plains, which affect the productivity of rice and the livelihoods of fishermen and farmers living in the coastal areas (Karolinoerita et al., 2020). This is compounded by scarce adaptive irrigation infrastructure, scarcity of access to climate resistant agricultural capital and technology and unequal institutional and extension capacity. These factors hinder the adoption of adaptive agricultural practices even though many adaptation technologies and strategies have been identified and proven to increase resilience in other contexts(Akter et al., 2025; Irham et al., 2022). Feedback from field studies in various provinces in Indonesia indicates that many farmers do indeed implement simple adaptations (adjusting planting times, changing varieties, managing planting intensity), but the scale and effectiveness of these adaptations are often hampered by problems of access to information, microfinance, and market institutions, meaning that the potential for reducing negative impacts has not been optimized(Yusriadi et al., 2024). From a global food system perspective, international reviews have found that without stronger greenhouse gas emission mitigation and targeted agricultural adaptation measures, global food production projections face a significant decline in the middle of this century, which will increase commodity supply uncertainty and also affect food prices and availability in importing countries such as Indonesia during certain periods.

Moreover, the literature demonstrates that the agricultural sector, per se, is a source of emission (through the use of fertilizers, land farming, and the emission of rice methane), which means that they should file a dual strategy: not only decrease the contribution of the agricultural sector to global warming but also make production systems more resistant to the inevitable (Yang et al., 2024). Policy-wise, there is an international call of incorporating adaptation and mitigation in the national plans through a combination of Climate-Smart Agriculture, restoring peatlands and mangroves and investing in water infrastructure and developing varieties resistant to climatic changes. This should be supported by sustainable financing systems, agricultural extension capacity building and social protection policies to the vulnerable farmers (Grigorieva et al., 2023; Musa & Ariff Lim, 2025).

Although there is increasing evidence of the effects of climate-agriculture interactions in Indonesia, there is a dearth of a synthesis that can bridge the biophysical effect, adaptive capacity on a farmer-level, and mitigation co-benefits of land. Furthermore, not many reviews put findings into context in Indonesia in Nationally Determined Contributions (NDCs) or appraise the interaction in adaptation and mitigation. The current study aims to help fill this gap by performing a systematic review of the existing empirical literature (2020-2025) to assess climate change effects on agricultural productivity, socio-technical adaptation barriers to climate change, and scalable adaptation-mitigation practices with dual benefits.

Method

This study is based on a Systematic Literature Review (SLR). The research process started by developing the corresponding literature which was further searched in the academic databases like Google Scholar, Sinta, ScienceDirect, and DOAJ using the keywords Climate Change, Global Warming and Agriculture and publications published within the last 2 years (2020-2025). The received articles were filtered in terms of inclusion criteria, which included climate change, global warming, and the effects of climate change, and in terms of exclusion criteria, including irrelevance to the topic or the inability to access the complete text. Articles which passed the requirements were also screeninged on the quality to determine the validity and applicability of the information. Some of the important information that was extracted was the objectives and methods of the research, the results and findings pertaining to the climate change and global warming and its impact on Indonesia.

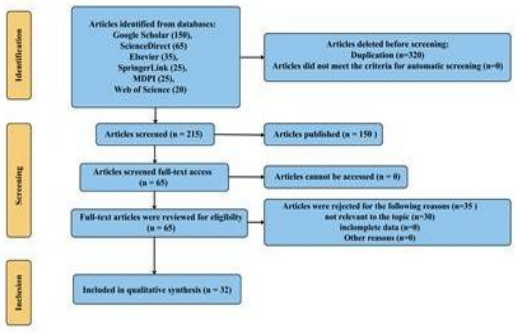


Figure 1. PRISMA Flowchart

The qualitative-descriptive approach was applied in the analysis of data, i.e. grouping of findings, comparison of results across the studies and synthesis of the information in order to obtain the overall picture of the effects of climate change and response measures in the agricultural sector of Indonesia. To ensure credibility and validity of the review, cross-verification of sources has been done and all the literature that has been selected has been verified as belonging to reputable and accredited academic publications. The SLR flow diagram was presented using the PRISMA (Preferred

Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al., 2021). The selection process resulted in 32 articles from a total of 320 initial articles after applying the inclusion and exclusion criteria.

Tabel 1. Inclusion and Exclusion Criteria

No.	Inclusion Criteria	Exclusion Criteria
1	Focuses on climate change/global warming impacts on Indonesian agriculture.	Irrelevant to climate change/global warming or Indonesian agriculture.
2	Empirical study, review, or analysis based in Indonesia or including it (e.g., ASEAN).	Focuses solely on other countries without data/implications for Indonesia.
3	Published between 2020–2025.	Published before 2020 or not officially released by end of 2025.
4	Full text available and legally accessible.	Only abstract available; full text behind paywall without institutional access.
5	Clear methodology: quantitative, qualitative, mixed, systematic review, meta-analysis, or modeling	Lacks clear methodology; only general statements without empirical/theoretical analysis.

Source: Filonchyk et al., 2024, *Science of The Total Environment.*

Result and Discussion

Definition and Mechanism of Climate Change and Global Warming

Climate change refers to long-term changes in weather patterns such as average temperatures, rainfall patterns, atmospheric circulation, dry and wet seasons, and the frequency and intensity of extreme weather events that occur over decades to centuries and are influenced by natural variability and human activities(Purify et al., 2024). Global warming is one of the most important aspects of climate change, namely the gradual increase in the average temperature of the Earth's surface, mainly due to the accumulation of greenhouse gases in the atmosphere that amplify the natural greenhouse effect(Abbass et al., 2022). Concentrations of CO_2, methane (CH_4), and nitrous oxide (N_2O) have increased significantly since the pre-industrial era, triggering the accumulation of heat energy in the global climate system and consequences for the Earth system, ecosystems, and human activities(15).

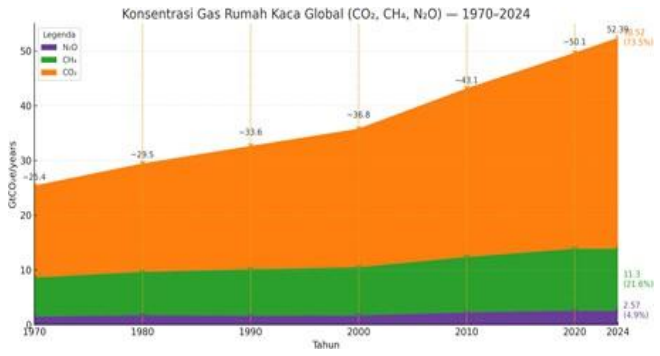


Figure 2. Global greenhouse gas concentration trends (CO_2, CH_4, N_2O) from the pre-industrial era to 2024.

Mechanistically, the Earth system operates through an energy balance: shortwave solar radiation enters the atmosphere and is partially reflected back, while the rest is absorbed by the surface and then re-emitted as longwave radiation. Greenhouse gases in the atmosphere, such as CO_2, CH_4, N_2O, and fluorinated gases, absorb some of this longwave radiation and re-emit it back to the surface, thereby increasing warming. As the concentration of these gases increases, a greater proportion of longwave radiation is retained in the atmosphere, causing an increase in the average temperature of the surface and lower atmosphere(Bibi & Rahman, 2023).

In addition, the climate system has a number of feedback mechanisms that can amplify warming, such as the melting of ice and snow, which reduces reflectivity; the release of carbon and methane from peatlands or permafrost that are beginning to thaw; and changes in cloud patterns and humidity that modify atmospheric circulation and radiation.

The Impact of Climate Change on the Food System

Climate change has become one of the greatest threats to the global food system. Rising average global temperatures, changing rainfall patterns, and increased frequency of extreme weather events have direct and indirect impacts on agricultural production, food supply stability, and the welfare of rural communities. Global warming has reached approximately 1.1–1.3°C above pre-industrial averages and will continue to increase if greenhouse gas emissions are not significantly reduced immediately.

These conditions not only disrupt agricultural production systems biogeophysically, but also trigger economic and social instability related to food availability and access in various regions of the world(Mirzabaev et al., 2023). Again, alterations in the rainfall pattern are one of the most concluding factors in agricultural production. Lack of predictability in planting periods, severe droughts, and too much rainfall lead to reduction in the productivity and higher losses of crops (Subedi et al., 2023). The agricultural instability in most of the tropical areas is also helped by the ever-growing intensity of El Nino and La Nina. The population of agricultural land under the risk of severe drought in the next 20 years in the world will exceed 60% in case emission tendencies do not decrease (Furtak & Wolińska, 2023). These effects are also felt where the earlier situations were relatively stable like the Southeast Asia and most of the sub-Saharan Africa.

Besides its influence on crop productivity, climate change also has an effect on the volatility of world food production and supply. High production variability leads to higher prices of food that are more unstable which jeopardize food security, particularly in developing nations. According to studies in climate economics, fluctuations in climate change in the yield of crops across the planet can decrease consumer surpluses in the US billions annually (Oishy et al., 2025). Rises in food prices due to drops in yields in one area may end up affecting other areas through international trade systems, thus, in other words, what happens in one area may cause food prices to boom world over. This highlights the need to have resilient food systems that are not affected by cross-regional climatic disturbances.

Climate change does not only affect the crop yields but also quality and nutritional value. Increased temperatures and perpetual drought decrease protein and other vital micronutrient content in food, including zinc and iron (Xu et al., 2024). As a result, the risk of malnutrition may increase, especially in developing countries that are highly dependent on single staple foods such as rice or corn. In addition, climate change also disrupts irrigation water supplies and reduces land productivity due to soil degradation. Declining water quality and soil erosion due to extreme rainfall exacerbate the loss of agricultural land fertility(Raj et al., 2022).

The agricultural sector plays a dual role in the context of climate change. As a source of greenhouse gas emissions and as a sector vulnerable to climate impacts, emissions from the agricultural sector include(Grohs et al., 2024) :

1. Land conversion and land use change that releases stored carbon as CO_2;
2. Methane emissions from flooded rice fields and livestock (fermentation and manure management);
3. N_2O emissions from nitrogen fertilizer use and soil organic matter decomposition.

The global agrifood system contributed a total of ~16.2 Gt CO_2eq in 2022, with 7.8 Gt CO_2eq coming from agricultural activities in crop and livestock production(Akiyama, 2024). In the business-as-usual scenario, agricultural emissions are likely to increase along with global food demand, but the mitigation scenario shows the potential for a decrease if sustainable agricultural practices are implemented.

The mechanism of climate change impact on agricultural systems involves several physical-biological pathways. First, more frequent heat stress and longer heat waves can disrupt plant growth, increase respiration, accelerate life cycle phases but reduce biomass accumulation and crop yields. Several agronomic models show that rising temperatures can shorten the plant growth period, resulting in imperfect seed formation or failure to fill(Shah et al., 2021). Second, changes in rainfall patterns and increased evaporation can reduce water availability for crops, exacerbate water deficits, and increase the risk of drought. The combination of high temperatures and drought will worsen crop damage. Third, extreme events such as floods, heavy rains, landslides, or prolonged droughts can damage crops, destroy irrigation infrastructure, and trigger soil erosion. Fourth, climate change impacts pests and diseases distribution in that warmer climate and varying humidity may lengthen pest generation cycles, increase their range, or cause new pests and diseases to occur in areas that were initially comparatively safe (L. Li et al., 2024).

Biophysical Impacts

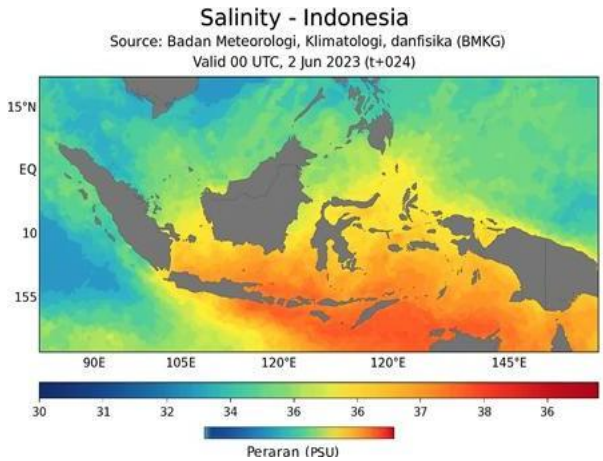


Figure 3. Map of Indonesia's agricultural vulnerability to climate change based on the Climate

Vulnerability Index (CVI). Source: Oelviani et al., 2023, Weather, Climate, and Society

Direct biophysical effects of climate change on the environmental conditions under which agricultural production occurs especially include temperature, patterns and intensity of rainfall, extreme weather conditions, sea level, soil status, pest and pathogen dynamics. Such biophysical pathways are likely to have more and more impacts on rice productivity, the resilience of an irrigation system, and the role of ecosystems in sustaining food production in Indonesia (Ansari et al., 2023). Extreme weather events also affect soil quality and function. Heavy rains and flooding accelerate erosion of the topsoil and remove nutrients, while periods of heat and drought accelerate the mineralization of organic matter, thereby altering long-term nutrient availability(Oishy et al., 2025). The impact on the soil microbiome alters nutrient cycling processes, resistance to soil diseases, and the soil's ability to support long-term productivity. International reviews and empirical studies conclude that weather-related microbiome disturbances can reduce the resilience of agricultural land and require proactive soil management interventions, namely the addition of organic matter and soil structure conservation(Mo et al., 2023).

Biophysical changes also modify the dynamics of pests, weeds, and pathogens. Increased temperatures and changes in moisture patterns can extend the reproductive season of insects, accelerate generations per year, and enable shifts in distribution areas to new altitudes or latitudes a phenomenon that has already been projected for brown planthoppers and several other pests in Southeast Asia/Indonesia(Surmaini et al., 2024). This increases the risk of outbreaks, adds to control needs, and potentially increases dependence on chemical inputs if integrated management strategies are not strengthened. Multi-stressor interactions also magnify biophysical impacts; for example, heat waves followed by drought will have a more severe synchronous effect than either impact alone, and flooding that causes saline intrusion can persistently reduce productivity if drainage and rehabilitation are not carried out quickly (Khairulbahri, 2021).

Productivity and Food Security

Based on a synthesis of the literature, rice productivity in Indonesia is projected to decline by 10–25% by 2050 due to an average temperature increase of 1–2°C(Ansari et al., 2023). In coastal areas of Java and Sumatra, land salinization has reduced rice yields by up to 30%(Oelviani et al., 2023). This decline in productivity has the potential to increase dependence on rice imports and exacerbate food inequality in rural areas. One of the main mechanisms of productivity decline is physiological disruption of plants due to heat stress. High temperatures during the flowering and grain filling phases cause sterility of rice panicles and a reduction in grain weight, as found in agronomic modeling by [9]. On top of that, the inability to predict at the beginning of rainy season compelled farmers to delay the process, which consequently shortened the growth time and decreased the amount of biomass (Khairulbahri, 2021).

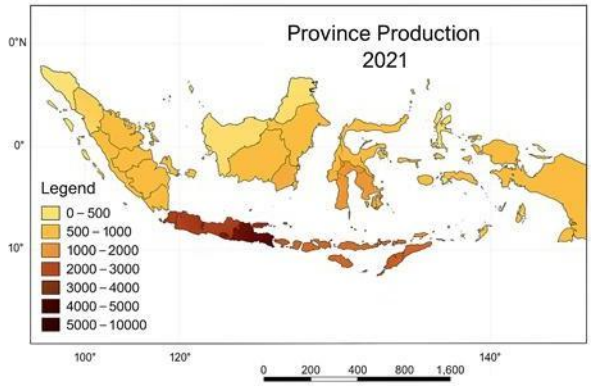


Figure 4. Rice production projections in Indonesia for 2021. Source: Ansari et al., 2023, Heliyon.

Pests and Diseases

Climate change does not only interfere with the physical environment in the agricultural setting, but it also substantially changes the biological processes of pests, diseases, and weeds- important constituents that define the success of the agricultural output. The rise in average temperature, humidity variations, and the frequency of severe weather conditions provide more favorable conditions under which organisms harmful to the plants develop and spread. Climate changes in Indonesia have increased the range of pests, and their life cycle has also been accelerated, having a direct effect on the growth of the severity of attacks and losses in agricultural yields.

The brown planthopper (Nilaparvata lugens), one of the greatest pests of rice, has been one of the most vivid illustrations, and now the highlands of Java and Bali are not safe as they used to be because it can also be found there. Projection studies have indicated that as the temperature rises by 1- 2 deg C, the possible range of brown planthoppers may rise by up to 40 percent in the mountainous areas of Central East Java. Warmer temperatures shorten the incubation period of eggs and accelerate metamorphosis, enabling these pests to complete 2–3 generations per growing season, compared to 1–2 generations under historical conditions(Surmaini et al., 2024).

In addition to planthoppers, stem borers and spider mites (Tetranychus urticae) also show increased

activity during extreme dry seasons, when plants experience water stress and become more susceptible to attack(L. Li et al., 2024). In the horticulture sector, armyworms (Spodoptera litura) are reported to be increasingly resistant to pesticides due to selection pressure accelerated by fluctuations in temperature and humidity(Subedi et al., 2023). Farmers' response to pest escalation generally still relies on chemical pesticides, which in the long term risk causing pest resistance, environmental pollution, and a decline in the biodiversity of natural enemies. Although the Integrated Pest Management (IPM) approach has been introduced nationally, its adoption is limited due to a lack of training, access to healthy seeds, and existing climate-based early warning systems(Mo et al., 2023).

Adaptation and Mitigation Strategies in the Agricultural Sector

Agronomic and Technological Practices

Technological and agronomic adaptations in agriculture are key to reducing the vulnerability of production to climate change while maintaining or increasing productivity(Zhao et al., 2023). The purpose of this adaptation is to be able to stay productive, and ensure food security and sustainability of agricultural systems under the growing influence of climate pressure which is becoming increasingly unpredictable in nature. One of such attempts to minimize the threat of yield drop and enhance the effectiveness of agricultural resources is the application of adaptive technologies and agronomic opportunities (Bhatnagar et al., 2024).

In different parts of the world, the research findings indicate that the application of Internet of Things (IoT) technology in smart irrigation, soil sensors, and microclimate have enabled farmers to become more efficient in their water use and streamline their planting schedules (Ishfaq et al., 2020).

This technology enables data-based agriculture, which is significant in addressing changing weather conditions and rainfalls (Gao et al., 2024). However, in Indonesia, the adoption of digital technology-based precision irrigation systems has also become an emerging phenomenon, particularly in drought-prone regions like East Java and Nusa Tenggara (Suriadi et al., 2022).

Furthermore, the agronomic adaptability measures, which include crop diversification, planting of climate-stress-resistant varieties, and conservative land management methods are also useful in sustaining productiveness (Grados et al., 2024). Dry rice species, including Inpari 30 Ciherang Sub 1 and Inpari 42 Agritan GSR has demonstrated a 20 percent increase in yields in regions with less rainfall (Noviana et al., 2021). Studies indicate that genotypes that have been bred to withstand hot environments can be useful in mitigating susceptibility of agronomical products to climatic changes (Liu et al., 2023; Yetgin et al., 2025).

At the socio-economic framework, technological and agronomic adaptation can only be successful based on the knowledge ability of farmers, their access to capital and technology, and institutional aids. Research states that community-based training and partnership between the government, universities, and the private sector play an essential role in expediting the process of adopting adaptive agricultural technologies (Okolie et al., 2024). Thus, the adaptation activities rely not only on the innovations at the technical level, but also on the social systems and policies that can facilitate the process of the agricultural transformation towards the sustainable development in the climate change era.

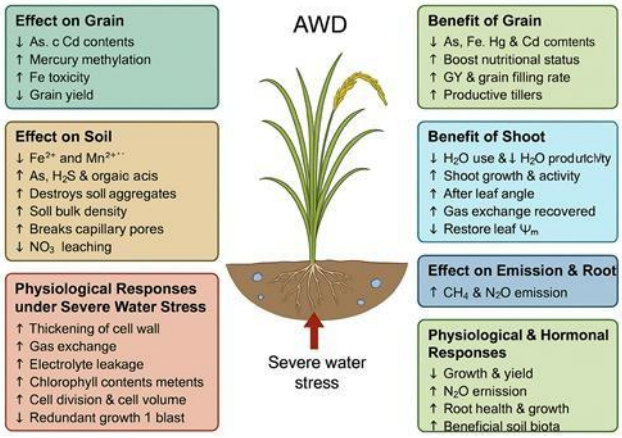


Figure 5. Schematic diagram of the AWD (Alternate Wetting and Drying) irrigation system for sustainable rice field water management. Source: Ishfaq et al., 2020, Agricultural Water Management

Mitigation Strategy

One of the primary sources of greenhouse gas (GHG) emissions in the world is agriculture, especially land clearance, enteric fermentation, livestock faeces and nitrogen fertilizer. It is approximated that this sector is responsible for approximately 20-25 percent of total world emissions (L. Li et al., 2024). Hence, the agricultural sector has mitigation strategies that are essential to the realization of Nationally Determined Contribution (NDC) targets and food security during climate change. The mitigation strategies should consider the differences in agrarian system of every country, agroecological, social and economic situations. Some of these mitigation measures that can be employed are:

Water Management in Rice Fields (Alternate Wetting and Drying)

The Alternate Wetting and Drying (AWD) have been cited as among the most effective mitigation

technologies of cutting the emission of methane (CH4) gases by rice fields. In this method the land is dried periodically and this will limit the anaerobic conditions and this will lower the production of CH4. As studies demonstrate, AWD that is used can cut CH4 emissions by 30-70 percent relative to fully flooded systems and does not have much impact on crop yields (Echegaray-Cabrera et al., 2024; Suwanmaneepong et al., 2023). The same research studies in Southeast Asia demonstrate that the efficiency of water use has increased up to 25 percent and still retained the productivity of rice (Anapalli et al., 2023). AWD needs to be applied with the assistance of farmer training, soil moisture sensing, and the alignment of AWD with the fertilization schedule to prevent the augmentation of N2O emissions by excessive oxidation (Hassan et al., 2022).

Optimization of Nitrogen Use

Nitrous oxide (N 2 O) is a GHG that is 298 times more efficient in global warming than CO2. To a great extent, these emissions are the results of the inefficient utilization of inorganic nitrogen fertilizers. The 4R Nutrient Stewardship (Right source, Right rate, Right time and Right place) -based mitigation measures have been found to be an effective approach for emissions reduction with no significant crop yield reduction (Fan et al., 2022). The practices of 4R can also decrease N_2O emissions by between 25 and 40% plus enhance the efficiency of nitrogen uptake reaching a maximum of 30% (Cui et al., 2024). Application of Ni-loaded fertilizers (e.g., slow- release, controlled-release, and nitrification inhibitor-coated urea) is also effective for inhibiting the soil net nitrification rate, leading to a 50% reduction in N2O emissions (S. Li & Tasnady, 2023).

Increased Soil Carbon Sequestration

(Murdiyarso et al., 2024). In addition, biochar can reduce N_2O emissions due to improved soil aeration and nitrogen retention(Novita et al., 2024). Biochar application contributed as much as 10 tons/ha to increase the soil's water retention capacity by 15% and reduce GHG emissions by up to 18%(Rivera & Chará, 2021).

Agroforestry and Land Restoration

The agroforestry approach integrates perennial crops with annual crops, providing dual benefits: carbon sequestration through biomass and increased soil biodiversity. This system can increase soil carbon stocks by up to 2.5 tons C ha^{-1} $year^{-1}$ in tropical regions(Lynch et al., 2021). In addition, peatland and mangrove restoration in Indonesia has proven to be a high-value mitigation strategy. Peat restoration using rewetting techniques can reduce CO_2 emissions by up to 80% compared to land that remains drained(Pratiwi, 2025). This effort is in line with Indonesia's national strategy to reduce emissions by 31.89% by 2030.

Mitigation of Enteric Methane Emissions in Livestock

Enteric fermentation in ruminants is the main source of CH_4 in the livestock sector. Mitigation is carried out by improving feed quality, administering additives such as tannins, vegetable oils, or Asparagopsis taxiformis seaweed, and implementing balanced nutrition-based feed management. Adding seaweed to cattle feed can also reduce CH_4 emissions by up to 50% without affecting productivity(Tuwaidan et al., 2024). However, the sustainability of this practice still requires evaluation in terms of cost, food safety, and local adaptation. In addition, increasing livestock production efficiency can reduce the intensity of emissions per unit of meat or milk produced.

1) Mitigation through Land Management and Integrated Policies

Agricultural mitigation cannot be separated from sustainable land use management. Reducing forest conversion to agricultural land and intensification of existing land with low-carbon practices are key strategies. Murdiyarso et al., (2024) show that controlling peatland clearing in Indonesia could avoid emissions of up to 1.2 $GtCO_2e$ per year. Integrated policy approaches, such as carbon credit schemes and strengthening Measurement, Reporting, and Verification (MRV) systems, will accelerate the adoption of evidence-based mitigation practices at the farmer level(Barbieri et al., 2024)..

Synthesis of Literature Findings

Table 2. Literature Findings

No	Author(s) (Year)	Focus	Key Finding	DOI
1	Ansari et al. (2023)	Climate impact on rice	+1–2°C by 2050 may cut yields by 25% in Java/Sumatra	https://doi.org/10.1016/j.heliyon.2023.e19639
2	Oelviani et al. (2024)	Coastal salinization	Sea-level rise reduces paddy yields by up to 30%	https://doi.org/10.1175/WCAS-D-23-0025.1

3	Surmaini et al. (2024)	Brown planthopper spread	Warming expands pest range to highlands, raising outbreak risks	https://doi.org/10.1016/j.jssas.2023.10.002
4	Irham et al. (2022)	Organic vs. conventional veg. farming	Organic farmers show higher resilience via diversification	https://doi.org/10.1155/2022/3590769
5	Yusriadi et al. (2024)	Local adaptation systems	Farmers adjust planting schedules but lack info/capital	https://doi.org/10.1038/s41598-024-72953-4
6	Khairulbahri (2021)	Rice supply instability (NTB)	Rainfall variability reduces yields, increases import reliance	https://doi.org/10.1016/j.heliyon.2021.e08515
7	Noviana et al. (2021)	Drought-tolerant rice	Inpari 30/42 boost yields by 20% in dry areas	https://doi.org/10.1088/1755-1315/648/1/012118
8	Murdiyarso et al. (2024)	Peatland GHG mitigation	Rewetting cuts CO_2 emissions by 80%; vital for NDCs	https://doi.org/10.1073/pnas.2307219121
9	Echegaray-Cabrera et al. (2024)	AWD in rice	Reduces CH_4 by 70%, saves 25% water, maintains yield	https://doi.org/10.3390/agronomy14020248
10	Fan et al. (2022)	Nitrogen efficiency	Enhanced fertilizers + 4R cut N_2O by 50%, raise N use by 30%	https://doi.org/10.3390/plants12010081
11	Karolinoerita et al. (2020)	Coastal salinity	Limits yields, restricts variety use, threatens food security	https://doi.org/10.21082/jsdl.v14n2.2020.91-99
12	Mohamed Shaffril et al. (2024)	Crop diversification	Enhances resilience to crop failure & price shocks	https://doi.org/10.1016/j.cliser.2024.100508
13	Mo et al. (2023)	Climate-driven crop diseases	Extreme rain worsens blast and bacterial wilt; early warning needed	https://doi.org/10.3389/fsufs.2022.1030540
14	Grohs et al. (2024)	Tillage & cover crops	Min-till + cover crops lower CH_4 and N_2O together	https://doi.org/10.1016/j.agee.2023.108747
15	Ishfaq et al. (2020)	AWD benefits	Water-saving, eco-friendly, yield-stable in SE Asia	https://doi.org/10.1016/j.agwat.2020.106363
16	Liu et al. (2023)	Heat-tolerant rice genes	*OsHTAS*, *TT1* improve thermotolerance without yield loss	https://doi.org/10.3390/ijms24087140
17	Omokaro et al. (2025)	Biochar use	Boosts water retention (+15%), cuts N_2O, raises SOC	https://doi.org/10.1016/j.farsys.2025.100167
18	Novita et al. (2024)	Peatland rewetting	CO_2 drops 80% within 2 years in restored oil palm peat	https://doi.org/10.1016/j.scitotenv.2024.175829
19	Okolie et al. (2024)	Smallholder adaptation	Info access, capital, and policy are key success factors	https://doi.org/10.1016/j.indic.2024.100451
20	Barbieri et al. (2024)	Adaptation–mitigation synergy	Integrated CSA delivers co-benefits with policy support	https://doi.org/10.1088/1748-9326/ad1629
21	Yuan et al. (2024)	Global crop impacts	Heat/drought cut grain yields by up to 25%; SEA highly vulnerable	https://doi.org/10.3390/agronomy14071360
22	Mirzabaev et al. (2023)	Food security risks	Up to 80M more at risk of hunger by 2050 without strong mitigation	https://doi.org/10.1016/j.crm.2022.100473

23	Bolan et al. (2024)	Soil contaminants	Floods/droughts increase heavy metals & pesticide residues	https://doi.org/10.1016/j.scitotenv.2023.168388
24	Xu et al. (2024)	Nutritional quality	Elevated CO_2 lowers rice/maize nutrition, raising malnutrition risk	https://doi.org/10.1016/j.ocecoaman.2024.107479
25	Grigorieva et al. (2023)	Global adaptation	EWS, stress-tolerant varieties, and CSA are most effective	https://doi.org/10.3390/cli11100202
26	Musa & Lim (2025)	Smart farming tech	IoT, soil sensors, and GIS cut emissions, improve input efficiency	https://doi.org/10.1108/IJCCSM-05-2024-0071
27	Defiyanti et al. (2024)	Rainfall forecasting	ARIMA-based forecasts improve planting timing, reduce crop failure	https://doi.org/10.25126/JTIIK.2024118682
28	Yang et al. (2024)	Land degradation	Climate change accelerates deforestation, erosion, biodiversity loss	https://doi.org/10.1126/science.adn3747
29	Bhatnagar et al. (2024)	CSA effectiveness	Participatory, localized CSA builds strong climate resilience	https://doi.org/10.1016/j.indic.2024.100535
30	Cui et al. (2024)	N_2O mitigation	4R practices can cut global cropland N_2O by 40%	https://doi.org/10.1016/j.oneear.2024.01.005
31	Li & Tasnady (2023)	Biochar carbon storage	Stores up to 10 t C/ha, enhances soil resilience	https://doi.org/10.3390/c9030067
32	Gabetto et al. (2025)	Rice-residue biochar	Suppresses N_2O, increases SOC in tropical soils	https://doi.org/10.1002/bbb.2734

Implications of the research

Synthesis findings indicate that climate change has reduced Indonesia's agricultural productivity through rising temperatures, rainfall uncertainty, coastal land salinization, and escalating pests, with projected declines in rice yields of up to 25% (Ansari et al., 2023; Yang et al., 2024) and up to 30% in coastal areas (Karolinoerita et al., 2020; Oelviani et al., 2023). Farmers generally rely on local adaptations such as adjusting planting times or changing varieties, but are hampered by limited access to information, capital, and technology (Okolie et al., 2024; Yusriadi et al., 2024). Implications for future research include three main directions:

1. Development of climate-stress-tolerant varieties (heat, drought, salinity) through gene-based molecular breeding such as OsHTAS and TT1(Liu et al., 2023), as well as strengthening the national seed system and field trials in various ecosystems(Noviana et al., 2021)
2. Strengthening participatory climate information systems that integrate rainfall predictions(Defiyanti et al., 2024) and pest outbreak forecasts(Surmaini et al., 2024) to support farmers' real-time decisions
3. Accelerating the adoption of land-based mitigation strategies such as Alternate Wetting and Drying (AWD), the 4R approach, and the application of biochar, which have been proven to reduce GHG emissions while improving reso urce efficiency(Echegaray-Cabrera et al., 2024; Omokaro et al., 2025). In the livestock sector, research on feed additives based on local seaweed (Asparagopsis taxiformis) needs to be evaluated in terms of sustainability and economic feasibility(Tuwaidan et al., 2024).

As a matter of policy, the integration of adaptation and mitigation must be strengthened in the Climate Change Adaptation Action Plan (RAAPI) and NDC through incentives for farmers, sustainable financing, and strengthening of MRV systems at the local level(Barbieri et al., 2024; Murdiyarso et al., 2024). A multidisciplinary approach combining technological innovation, variety research, and evidence-based policies is key to transforming Indonesia's agricultural system to become more climate resilient.

Conclusion

Climate change has and will continue to disrupt Indonesia's agricultural system through increased temperatures, rainfall uncertainty, land salinization, and escalating pests and diseases. Local adaptation by

farmers, such as adjusting planting times or changing varieties, is still limited by access to climate information, capital, and technology. On the mitigation side, practices such as AWD, the 4R approach, peatland restoration, and agroforestry have proven effective in reducing emissions while increasing land resilience. To that end, the government needs to strengthen the integration of adaptation-mitigation policies in national programs such as the Climate Change Adaptation Action Plan (RAAPI), expand the reach of evidence-based extension services, and allocate sustainable funding for research on climate-resistant varieties and adaptive irrigation infrastructure. Without collective cross-sectoral efforts, national food security will become increasingly vulnerable to future climate shocks. This review is limited by its focus on English and Indonesian literature (2020–2025), potentially omitting relevant grey literature or studies in other regional languages. Moreover, publication bias toward positive adaptation outcomes may overestimate effectiveness. Nonetheless, this study provides a robust, policy-relevant synthesis that underscores the urgency of integrating adaptation and mitigation into Indonesia's agricultural development agenda.

Acknowledgements

I want to sincerely thank my supervisor, my co-authors, and everyone else who helped me finish this work. I hope that this work will advance scientific understanding in the future.

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