Implementation of Regenerative Technologies for Sustainable and Net-Zero Rice Farming in Adapting to Climate Change in Indonesian Coastal Areas

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Abstract. Success in achieving Indonesia's dream of food security is faced with various significant challenges in line with climate change, which impacts sea level rise, salinity intrusion, and unpredictable weather patterns. These factors cause a decrease in rice production and salinization of rice fields in coastal areas. Regenerative technologies present a viable solution for achieving sustainable, net-zero rice farming (NZF) while enhancing resilience to climate change. This study comprehensively assesses the implementation of these technologies in Indonesian coastal regions. A bibliometric analysis and a summary of innovative agricultural methods, such as the System of Organic-Based Aerobic Rice Intensification (SOBARI), also known as IPATBO, highlight their effectiveness in improving rice yields and soil health. Results from regenerative technology demonstrations (2007–2024) show improved soil health and increased fertilizer and water efficiency, reducing inorganic inputs by 25–50% and water use by 30–40% while raising rice productivity by 25–50%. Adopting eco-friendly practices, including algal biofertilizers and compost, has further enhanced soil health. In addition, the practice of the NZF system in Indonesia will support Indonesia's targets in reducing greenhouse gas emissions and carbon absorption.

1 Introduction

Coastal rice cultivation is highly vulnerable to climate change impacts such as rising sea levels and unpredictable weather patterns, causing seawater intrusion into crop areas. This can endanger soil health and reduce crop productivity [1]. On the other hand, rice plants have a narrow tolerance range to salinity, so seawater intrusion can inhibit rice plant growth and yields [2]. Furthermore, unstable weather patterns cause changes in rainfall distribution and extreme temperature fluctuations, making planting and harvesting times more uncertain [3].

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These factors are a challenge for rice cultivation in coastal areas. These factors can cause crop failures, which will impact farmers' income.

Rice farmers in coastal areas of Indonesia encounter a complex array of challenges that significantly impact their agricultural productivity and economic viability. Climate change manifests through increased frequency and intensity of extreme weather events, such as prolonged droughts and flooding, which disrupt planting schedules and diminish rice yields to 50%, especially in Southeast Asia [4]. Additionally, rising sea levels and heightened salinity due to saltwater intrusion adversely affect soil quality and crop health, further complicating agricultural practices [5]. Most farmers still rely on conventional farming methods that are less able to adapt to the dynamics of the ever-changing environment. In addition, low rice prices in the market worsen the economic conditions of rice farmers in coastal areas [6]. To overcome this problem, a comprehensive approach is needed, such as regenerative technologies for sustainable and net-zero rice farming in adapting to climate change in coastal areas of Indonesia.

Net-zero farming is deeply interconnected with sustainable agriculture, as both aim to enhance environmental stewardship while ensuring food security and economic viability. Net-zero farming reduces greenhouse gas emissions from agricultural practices, responsible for approximately 23% of global emissions, while sustainable agriculture emphasizes practices that maintain ecological balance and promote biodiversity [7]. By implementing regenerative practices, farmers can sequester carbon and improve soil health and resilience to the impacts of climate change [8]. This approach aligns with sustainable agriculture's goals by encouraging farming systems that are environmentally friendly, economically viable, and socially just. In addition, net-zero farming is expected to support rice cultivation, especially in coastal areas, in facing the challenges of climate change so that crop productivity remains high and the use of agricultural resources can be carried out efficiently [9]. This study examines regenerative technology's application to support sustainable and net-zero rice farming practices in Indonesia's coastal areas. Specifically, the study aims to assess the effectiveness of innovative agricultural methods, such as IPATBO, across Indonesia (2007–2024) in reducing greenhouse gas emissions while improving rice yields and soil health. This research links regenerative technologies with Indonesia's Climate goals.

2 Methodology

This research was carried out using a combination method, namely bibliometric analysis and a summary of the results of the research that has been carried out (Table 1). Bibliometric analysis was carried out to identify key trends in regenerative rice farming using data sources from ScienceDirect (2020-2024). The research summary comes from research activities carried out previously in the form of research on organic biofertilizers and Water-Saving Technology (2007-2024).

Table 1. Summary of Methodology

Method	Objective	Data Source	Implementation
Bibliometric Analysis	Identify key trends in regenerative rice farming	ScienceDirect (2020-2024)	Search terms: "regenerative agriculture," "climate change," "coastal rice farming," analyzed using VOSviewer
Organic-Biofertilizer & Water-Saving Technology	Improve soil health and water efficiency	Experimental plots (Indonesia, 2007-2024)	Use of IPATBO system, bioameliorants, and water-efficient techniques

2.1 Data retrieval for bibliometric analysis

Data for this bibliometric analysis were collected from the ScienceDirect database. The search terms and their combinations included 'regenerative,' 'agriculture,' 'rice,' 'farming,' 'sustainable,' 'climate change,' 'coastal,' 'low-emission,' and 'technologies.' The search was restricted to research articles published between 2020 and 2024 in agriculture and biological sciences. Publications were further limited to open-access English-language articles. The detailed search strategy is presented in Table 2. Bibliographic data from the search results were exported in RIS format and analyzed using VOSviewer 1.6.19. The term occurrence threshold was set to 15, resulting in 83 terms being visualized.

Table 2. Search strategy used to retrieve relevant research articles

Search Strategy	Science direct
Regenerative AND agriculture AND rice AND farming	142
Sustainable AND rice AND cultivation AND practices AND indonesia	136
Climate AND change AND adaptation AND coastal AND rice farming	82
Low-emission AND technologies AND rice AND production AND indonesia	78
Rice AND farming AND rising AND sea AND levels	91
Coastal AND climate-smart AND rice AND farming AND technologies	24

2.2 Organic-biofertilizer and water saving technology

This article utilizes a review method by synthesizing secondary data from implementing an organic-based aerobic rice intensification system (IPATBO) in Indonesia from 2007 to 2024. The rice cultivation practices under the IPATBO system were carried out on approximately one-hectare experimental plots. The IPATBO method involved preparing the land and managing the soil, along with constructing drainage channels measuring 20 cm in width and 10 cm in depth, spaced every 4 meters within the plot to control water levels. These channels were also designed to manage excess water. Fertilizer management in the IPATBO system was carried out in an integrated manner, utilizing 2-3 tons per hectare of rice straw compost, 500-1000 kg of rice husk biochar, 0.4-1 kg of biofertilizer in combination with inorganic fertilizers and organic liquid fertilizers [10].

3 Result and discussion

3.1 Bibliometric analysis

VOSviewer was utilized to analyze bibliometric data and uncover emerging research themes and trends from the past five years. Figure 1 presents a co-occurrence map of keywords generated using the complete counting method with an overlay visualization. A minimum occurrence threshold was applied to author keywords in the research articles to pinpoint the most relevant keywords, resulting in identifying the top 48 keywords. These terms provide a clear picture of the current research focus on coastal rice farming under the stress of climate change. Notably, there are clear distinctions among studies concentrating on strategies for coastal rice agriculture facing climate change, with topics such as effect, climate change, production, productivity, farmer, policy, framework, and community. The keywords "climate change and production" seem central, linking all related themes.

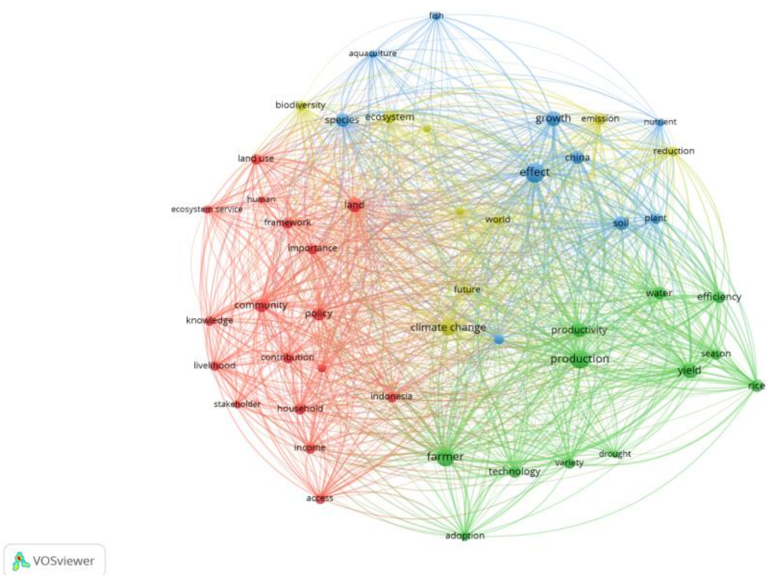

Fig. 1. A network visualization of the co-occurrence mapping of pertinent keywords related to research on coastal rice farming under the stress of climate change

The bibliometric analysis categorizes research on coastal rice farming under climate change stress into four interconnected clusters (Table 3), with minimal variation in the associated keywords. Observing the publication timeline in Figure 2, it becomes clear that research on food production is a relatively recent focus. Toward the end of 2022, studies concentrating on developing drought-resistant rice varieties to sustain yields and biodiversity while emphasizing ecosystem services became more prominent (yellow color). Although reports from 2023 to 2024 are not shown in Figure 2 due to their limited occurrence, this indicates a decline in publications from 2023 to 2024 compared to 2020–2022.

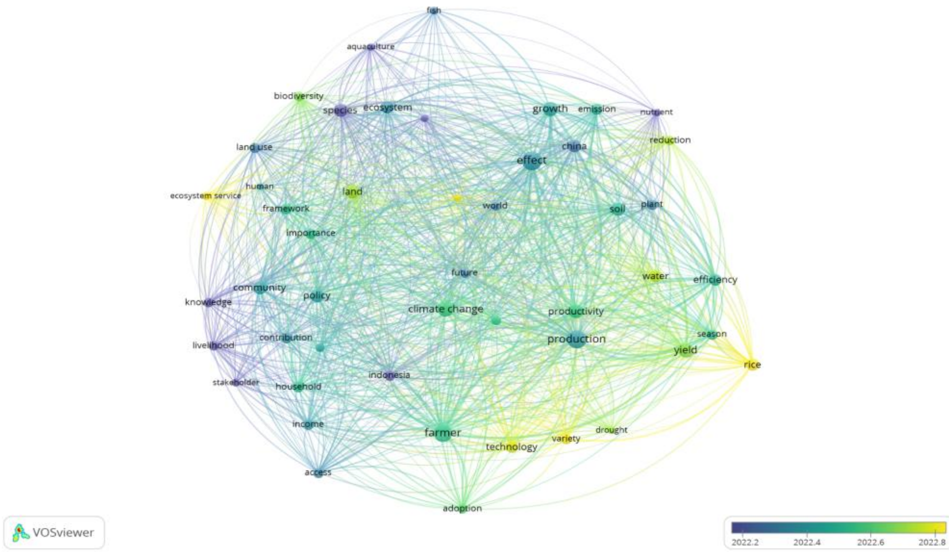

Fig. 2. An overlay visualization of the publication year mapping related to research on coastal rice farming under the stress of climate change

Table 3. A selection of terms organized into clusters according to the analysis of textual data

Cluster 1 (17 items)	Cluster 2 (12 items)	Cluster 3 (10 items)	Cluster 4 (9 items)
access, community, contribution, ecosystem service, framework, household, human, importance, income, indonesia, knowledge, land, land use, livelihood, policy, resilience, stakeholder	adoption, drought, efficiency, farmer, production, productivity, rice, season, technology, variety, water, yield	aquaculture, bangladesh, china, effect, fish, growth, nutrient, plant, soil, species	agriculture production, biodiversity, climate change, ecosystem, emission, food production, future, reduction, world

3.2 IPATBO technology

The rice cultivation practice using the IPATBO system can increase rice yields by 25–200% compared to traditional flooded irrigation systems, as shown in Table 4. Recent trials conducted in 2024 at the Demoplot in Warung Kiara, Sukabumi, West Java, demonstrated that IPATBO can enhance yields by 25–50%, achieving 10–12 tons per hectare. IPATBO technology has been shown to improve outcomes by at least 25% compared to conventional methods. This increase occurs because IPATBO can improve soil health by increasing cation exchange capacity (CEC), organic carbon content, and beneficial microbial biodiversity. Furthermore, it reduces inorganic fertilizer usage by at least 25% and improves irrigation water use efficiency by 30–40%. These findings suggest that agroecology-based farming practices can sustainably enhance soil health and rice productivity [11].

The IPATBO system practice is environmentally friendly and sustainable because it utilizes the presence of waste in the community. IPATBO uses materials that can replace inorganic fertilizers, such as rice husks and straw, as compost. Freshly harvested rice straw contains 0.5–0.8% nitrogen, 0.07–0.12% phosphorus, 1.16–1.66% potassium, 0.05–0.1% sulfur, and 4–7% silica. Utilization of this waste can reduce the use of inorganic fertilizers by up to 25%. This is because the macronutrient content in rice straw is high, namely 40% nitrogen, 30% phosphorus, and 80% potassium. Rice plants can absorb these macronutrients to support their growth and development, reducing the need for fertilizer for the next crop.

Table 4. The summarized harvested rice yield of IPATBO in different locations in Indonesia

Years	Different districts across provinces in Indonesia	Grain yield (ton ha^{-1})	Increment to conventional
2007-2015	Bali, NTT, Banten, West Java, Central Java, East Java, North Sumatera, South Sulawesi, and North Sulawesi	7.0-11.0	50-200%
2016-2017	South Sulawesi (22 District), West Java (Ciamis, Garut, Cianjur, Karawang), and North Sumatera (Binjai, Deli Serdang, Samosir)	6.0 -10.4	25-100 %
2018	North Sumatera (Binjai, Deli serdang, and Langkat), Bali (Buleleng), and East Java (Jepara, Nganjuk)	6.5-9.6	25-50 %
2019	Demoplot in SPLPP Ciparay Bandung	7-7.5	25%
	Demoplot IPATBO, South Sulawesi 2021	8.5	25%
2021-2022	Demfarm Bangkinang, Riau with 114 farmers	7-9	50-100%
2022-2023	Demoplot Bone Bolango (Gorontalo), SPPL-Ciparay (West Java), Bantul (Yogyakarta)	7-9	25%
2014-2024	Demoplot Cikande, Serang (West Java)	8-10	25-40%
2024	Demoplot Warung Kiara Sukabumi, West Java	10-12	25-50%
	Demoplot SPLPP-Ciparay Bandung, West Java	8-10	25%

3.3 Agroeco-friendly technology for net-zero farming

3.3.1 Biofertilizers and organic soil enhancers

Rice farming in Indonesia's coastal areas faces challenges due to climate change, such as flooding and soil salinity. Net-zero farming can be used as an approach to adapting to these conditions. Biofertilizer is a solution to improve soil health and crop yields and reduce dependence on chemical fertilizers. A biofertilizer contains live microorganisms that colonize the rhizosphere and promote plant growth by enhancing nutrient availability to the host plant when applied to soil, seeds, or plant surfaces. Common biofertilizers include phosphate-solubilizing bacteria like *Pseudomonas* sp., nitrogen-fixing bacteria like *Azotobacter* and *Rhizobium*, arbuscular mycorrhizal fungi, and nitrogen-fixing cyanobacteria such as *Anabaena*. Biofertilizer formulations often include cellulolytic bacteria and microorganisms that produce phytohormones like auxin and cellulase enzymes. The application of enriched Azolla extract (EAE) biofertilizers significantly increased rice grain yield by 37.06% compared to control plots in flood-prone coastal areas [12].

3.3.2 Climate-smart water management

Climate-smart water management optimizes water use in rice cultivation to increase efficiency, reduce environmental impact, and adapt to climate change. Controlled irrigation and water-saving techniques are essential for rice cultivation when water is scarce. The application of manure can reduce the negative impacts of water shortages. This occurs by increasing nutrient availability, improving soil properties, and encouraging plant growth. Controlled irrigation, such as the Alternate Wetting and Drying (AWD) method, can reduce water use by periodically flooding and drying the land. Water-saving methods include direct sowing instead of planting seedlings and reducing water consumption during planting [13].

3.3.3 Climate change mitigation

Building SOM is one of the most effective strategies for carbon sequestration in agricultural systems. Soils rich in organic matter can store significant amounts of carbon dioxide (CO_2), thus mitigating climate change impacts. Research indicates that every 1 Mg C ha^{-1} increase in SOM can potentially enhance rice production by 10–50 kg ha^{-1}, highlighting the dual benefits of increased productivity and carbon storage [14]. Organic farming practices that enhance SOM can also reduce greenhouse gas emissions associated with rice cultivation. For instance, integrating organic amendments has been shown to lower methane (CH_4) emissions from flooded rice fields while maintaining or increasing yields. This is crucial as rice paddies are significant sources of CH_4 due to anaerobic decomposition processes. Soils with high organic matter content are more resilient to climate variability, including droughts and floods. By improving soil health and structure, these soils can better withstand extreme weather events, ensuring stable crop production even under changing climatic conditions [15].

4 Conclusion

IPATBO has improved soil health and increased fertilizer and water efficiency, reducing inorganic inputs by 25–50% and water use by 30–40% while raising rice productivity by 25–50%. Adopting eco-friendly technologies such as algal biofertilizers, compost, goat manure, and biofertilizers alongside crop management practices (cropping systems and salinity-adapted rice varieties) has significantly enhanced soil health and boosted rice yields. NZF aligns with Indonesia's goal of reducing greenhouse gas emissions and achieving net-zero carbon by enhancing carbon sequestration in coastal rice paddies. Integrating organic and water-saving biofertilizers into agricultural systems can increase the resilience of sustainable rice farming in coastal areas to climate change. For broader technology adoption, policymakers are focused on providing financial support, strengthening agricultural extension programs, and aligning regenerative practices with national climate goals. Future research must further explore microbial interactions in soil, refine biofertilizer formulations, and assess long-term drought impacts. By integrating this innovative approach, Indonesia can achieve sustainable net-zero rice farming and food security amidst future climate change.

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