sustainability

Review

Indonesia Rice Irrigation System: Time for Innovation

Rose Tirtalistyani [1,2,*], Murtiningrum Murtiningrum [2] and Rameshwar S. Kanwar [1]

[1] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA
[2] Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia
* Correspondence: rose.tirtalistyani@ugm.ac.id

Abstract: Indonesia is likely to face a water crisis due to mismanagement of water resources, inefficient water systems, and weak institutions and regulatory organizations. In 2020, most of the fresh water in Indonesia was used for irrigation (74%) to support the agricultural sector, which occupies 30% of the total land area in Indonesia. Of all agricultural commodities, rice is one of the major and essential commodities, as it is the basic staple food for almost every Indonesian. However, in 2018, the Ministry of Public Works and Housing (MoPWH) reported that 46% of Indonesian irrigation infrastructure is moderately to heavily damaged. Looking at how irrigation can be very crucial to the welfare of Indonesian population, this study conducted an extensive literature review of the historical, current, and future management of irrigated rice production systems in Indonesia. This study has clearly shown that the irrigation systems in Indonesia have existed for thousands of years and, thus, there is a close relationship between irrigation and the socio-cultural life of the Indonesian population. Aside from how climate change influences water availability for irrigation, rice production with a constant water ponding system has been found to contribute to climate change, as it emits methane (CH_4) and other greenhouse gases from agricultural fields of Indonesia. Therefore, the required modernization of irrigation systems in Indonesia needs to consider several factors, such as food demands for the increasing population and the impact of irrigated agriculture on global warming. Multi-stakeholders, such as the government, farmers, water user associations (WUA), and local research institutions, need to work together on the modernization of irrigation systems in Indonesia to meet the increasing food demands of the growing population and to minimize the impacts of agriculture on climate change.

Keywords: Indonesian irrigation systems; rice production; food security; greenhouse gas emissions

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1. Introduction

Water has always been an important source for any society to survive on this planet, and it is also vital for the survival of animals and plants. In recent years, water has become a precious source for food and energy production. At the same time, readily available water for agriculture and energy has become more and more scarce. The threat of a water crisis for drinking and sanitation has been long known as a global sustainability problem, and, thus, each of us needs to use and manage water mindfully and sustainably. Despite being one of the ten water-rich countries in the world, Indonesia is not exempted from these threats [1]. Indonesia is likely to face a water crisis due to water mismanagement, as evidenced by high levels of water pollution, inefficient water usage, and weak institutions and regulatory systems [2,3].

Based on the Food and Agricultural Organization (FAO) data, Indonesia was responsible for up to 8.4% of the total world's water usage in 2019 [4]. Out of the total water usage, agriculture is one of the most essential and important sectors, and consumes most of the available fresh water in Indonesia. In 2020, fresh water in Indonesia was mostly allocated for irrigation (74%), with the rest going to household, urban, and industrial uses (11%), rivers (12%), reservoirs, and ponds (3%) [5,6]. A World Bank report mentioned that the agricultural sector contributed about 13.3% of the total GDP of Indonesia in 2021 [7]. The agricultural sector employs 38 million people [8] and covers almost 30% of the total agricultural area in Indonesia [9]. It also has become the primary source of income for rural areas, where 13% of Indonesia's poor lives [10]. Water management and irrigation are critical inputs to agriculture that significantly impact food output and could also help reduce greenhouse gas emissions from agriculture if managed judiciously. Many developing countries in the world are facing a water crisis due to their heavy reliance on water use for agricultural production [11].

Rice has been placed as one of the most important agricultural products among many agricultural commodities, as it has become the primary staple food for most Indonesians. Indonesia is the third-largest rice producing country in the world, following China and India [12]. The increase in rice production in Indonesia grew simultaneously with the development of irrigation infrastructure. Indonesia achieved its first self-sufficient rice production in 1984 after a massive land shift to agriculture and the successful construction of irrigation systems between 1969 and 1989 [13]. In 2004 and 2008, Indonesia achieved its second and third periods of self-sufficient rice production. Indonesia's infrastructure, including research and development (R&D) and governmental policies, have played an important part in supporting the dynamics of rice production [14]. Indeed, the FAO reported that 6.7 million hectares of paddy fields rely on the irrigation system [12]. Indonesia is now included in the list of rice importers [15].

Substantial irrigation infrastructures in Indonesia have been damaged in the last two decades, leading to inefficient water delivery and water use by crops. According to Azdan [16], 22% of the overall irrigation system in Indonesia was found to be moderate to heavily damaged in 1999. This number increased at a rate of 20% in 11 years, while, in 2010, the percentage of moderately and heavily damaged irrigation infrastructure reached 52%. As of 2018, according to the Ministry of Public Works and Public Housing (MoPWH), Indonesia has a total of 7.1 million ha of under surface irrigation networks, with 46% of the irrigation systems being damaged. Ministerial Regulation of MoPWH No. 12/PRT/2015 defines a moderately damaged irrigation system as one where 21–40% of the infrastructure and channel conditions are damaged from their initial state, whereas a heavily damaged system is when more than 40% of them are damaged.

The existence of irrigation has long been associated with reducing poverty [17–20] and assuring food security [21–23]. The presence of a simple irrigation system is valuable for boosting agricultural food security, especially during the dry season [24,25]. It has an essential role in assisting farmers in adapting to climate change, increasing household income, and attaining food security [26]. In Indonesia, the vast development of the irrigation system from the 1970s to 1990s has evidently decreased poverty, which has dropped from 40.8% to 11.4% of the poor population [27,28]. Damayanti [29] reported that the irrigation system in Parigi Muotong, Indonesia, could boost small-scale paddy farming production by 3.98% and farmers' incomes by 1.44%. Therefore, it is clear that water resource management to ensure food security and community well-being can be hampered by poor irrigation systems. Looking at how irrigation is closely related to the welfare of the Indonesian people, this paper aims to provide an extensive literature review of the historical, current, and proposed future irrigation systems in Indonesia. This study also reviews how policies and stakeholders' involvement can help in assuring food security, mitigating greenhouse gas emissions, reducing irrigation water losses, and helping to improve farmers' incomes in Indonesia.

2. Study Area

Indonesia is the largest archipelago in the world, located in southeastern Asia, between the Indian Ocean and the Pacific Ocean (Figure 1). It has 17,508 islands, 6000 of which are inhabited. This country has an area of 1.9 million km^2, with 76% of it being occupied by water. The climate in Indonesia is tropical, characterized by hot temperatures and a lack of rainfall during the dry season, and very high precipitation during the wet season, with several occurrences of severe storms (rain intensity > 150 mm hr^{-1}). The annual rainfall of this country falls between 2000 to 3500 mm, depending on the region [30] and climate patterns, such as La Niña and El Niño [31,32]. Rain falls mainly during the October–March period, with a mean annual temperature of 25.8 °C. The Indonesian Statistical Agency (*Badan Pusat Statistik*) reported that the population of Indonesia in 2020 was 270.20 million people, placing Indonesia as the fourth most populous nation in the world [10]. The growing population with uneven distribution in space on thousands of Indonesian Islands has put pressure on Indonesia to improve water management for agriculture. On Java Island, the main economic hub where about 60% of the total Indonesian population lives, just 4% of the island's total water supply is accessible, mainly because of the country's rainfall patterns [5].

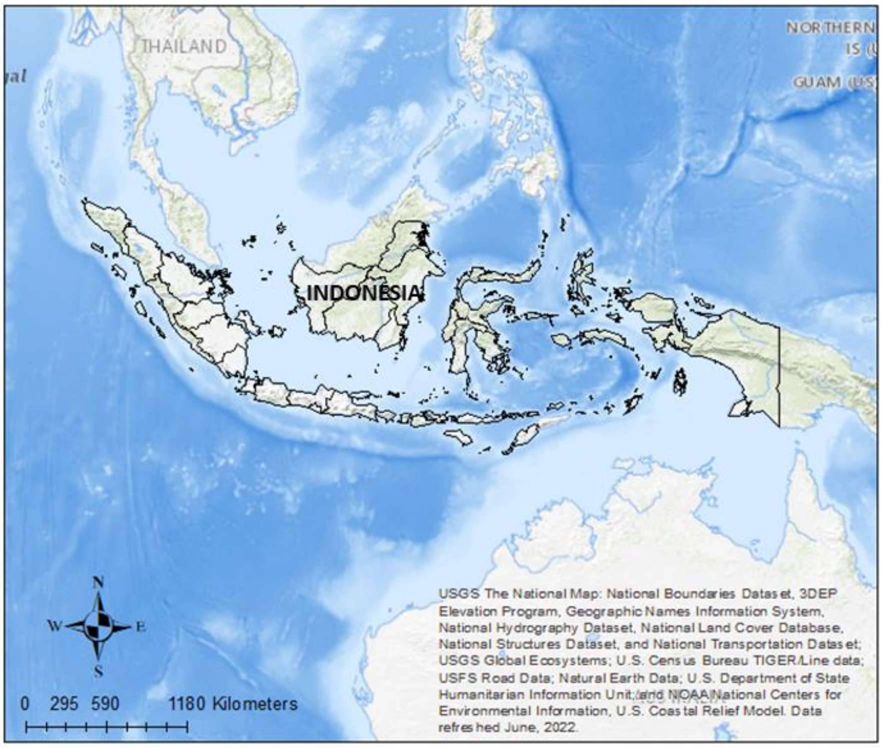

Figure 1. Map of Indonesia.

In terms of water resources, Indonesia has been considered as one of the ten countries with abundant water globally [1]. The FAO reported that Indonesia's annual renewable water resource (RWR) is 103.59 cm/year from surface water and 23.99 cm/year from groundwater. These numbers are slightly lower than the typical water needed for irrigated rice cultivation, where IRRI reported that 130–150 mm is the typical water quantity needed to irrigate rice crops in Asia [33]. More than 85% of the land in Indonesia is covered by vegetation [34]. Rapid changes in land-use, especially on Java Island, have reduced paddy fields in Indonesia in the last 10 years. Currently, 11 million hectares of area in Indonesia are planted as paddy fields, and 63% of the paddy area is irrigated (Figure 2). The irrigation system in Indonesia has thousands of years of history, with a close relationship to culture [35–37]. Therefore, irrigation is considered an essential infrastructure for water management in Indonesia. Based on the Indonesian Government's Medium-term Development Plan 2020, Indonesia will still develop its additional irrigation capacity by constructing new irrigation systems to irrigate an additional 500,000 ha of paddy fields between 2020–2024 [38].

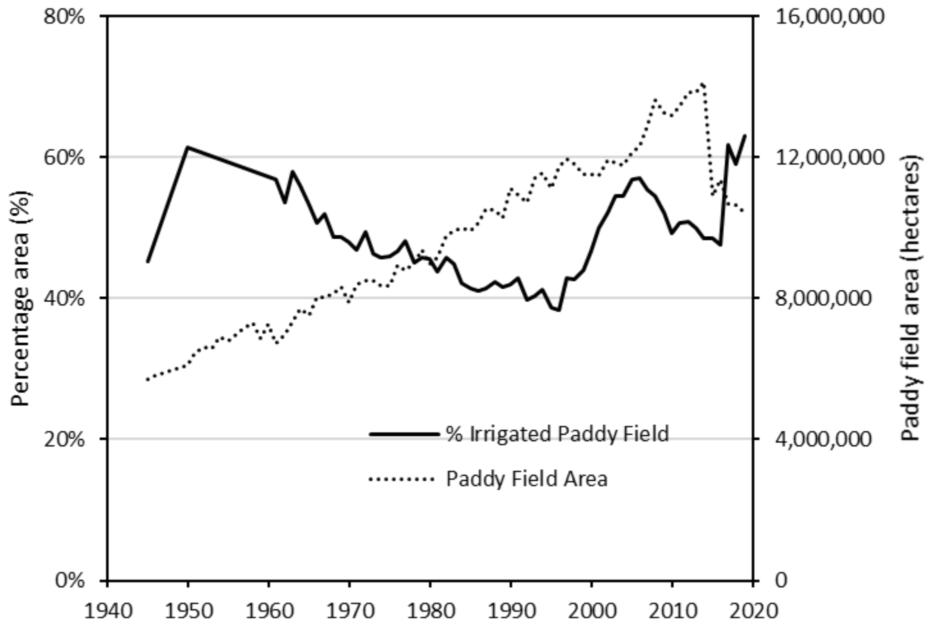

Figure 2. Paddy field area and percent irrigated from 1945 to 2019 (Data retrieved and modified from [39–41], www.fao.org, and www.irri.org accessed 30 June 2022).

3. Indonesia's Rice Irrigation System

3.1. History of Irrigation System and Irrigation Infrastructure Development in Indonesia

The development of rice farming is believed to have existed in Indonesia since 1600 BC [42]. Irrigation systems in the form of basic canals are estimated to have existed on the island of Java during the first century. These canal systems were initially tiny in size, but were within the capacity of local populations to sustain themselves for generations. Dutch colonialism in Indonesia began in 1602, when a Dutch trading partnership was formed called *Vereenigde Oostindiche Compagnie* (VOC). The VOC focused on agricultural development to obtain the highest benefits from Indonesian agricultural products, especially spices. Trials of large-scale irrigation development with longer-lasting construction began in the mid-nineteenth century on Java Island in an effort to alleviate the starvation caused by the prolonged drought in the Demak district in 1849 [43]. Around 280,000 people died from the famine that year. Since then, weirs have been built in various locations, including Gelapan, Tuntang, and Sidoarjo, to support irrigation systems and infrastructure [40,44,45].

Around the end of the nineteenth century, irrigation development was closely related to political tools for the colonial government's efforts to produce export commodities associated with "*cultuurstelsel*" or enforced planting of selected commodities, mainly sugarcane, which required irrigation. The Dutch Government made irrigation one of the policy instruments in implementing political ethics (*Ethiesche Politiek*), which Queen Wilhelmina announced in front of the Dutch parliament at the beginning of the twentieth century [46]. Political ethics is another term for the moral justification of political activity that was enforced on the Indonesian people [47]. The establishment of political ethics was a result of concerns by the European aristocracy, who pledged to recompense the Indonesian people for previous political decisions, such as enforced planting [46]. Another goal of irrigation development at that time was to overcome poverty and continue the agricultural surplus on Java Island to benefit the Dutch economy. The political development in irrigation was also influenced by the advancement of hydraulic technology, which enabled the construction of irrigation systems on a larger scale [40].

As a result of the Dutch strategy of adopting political ethics, the first quarter of the twentieth century (1900–1925) was described as an era of large-scale irrigation growth and the establishment of government-based irrigation management organizations. One of the substantial developments was the formation of an irrigation committee. The concept of irrigation management was founded in 1871 by a commission led by R. De Bruyn. As a result of the commission's report, the irrigation brigade was founded in 1885 as a particular unit under the *Burgerlijke Openbare Werken* (BOW) that oversaw the Government's irrigation systems [46]. With the increase in irrigation development, irrigation brigades were considered insufficient. In 1889, the irrigation brigades were replaced with irrigation area units (*irrigatie afdeling*) within a river basin region [48]. In 1906, a commission was constituted to draft levies and monthly payments from the plantations to assist financial authorities in managing water distribution and implementation of policies, which served as the predecessor of the irrigation committee founded in 1920.

The second stage (1925–1950) was a period of intensifying irrigation water management at the tertiary canal level to support the agriculture plan in a small-scale region [42]. To help with water distribution, water intake infrastructures were created to control and regulate irrigation water supplies at the tertiary canal level in irrigated sugarcane fields. Farmers were hired as village-level representatives for the water management organizations [39]. Although this decentralization process in the Java province began in 1926 and irrigation affairs were handed over to the provincial government in accordance with the decentralization process, a law regulating irrigation as a whole (*Algemeen Water Reglement*) was only announced in 1936, which the Provincial Water Regulation policy later followed [48].

To address the issue of food insecurity and in response to the introduction of green revolution technologies in the late 1960s, Indonesia's water resource development went through a series of five-years development programs, which included the restoration of the previous outdated systems as well as the extension of existing irrigation systems to neighboring islands [49,50]. Irrigation investment was made on a large scale in the 1970s and 1980s with the goal of establishing rice production self-sufficiency in Indonesia [51]. The availability of water-responsive green revolution technology necessitated the upgrading of irrigation infrastructure and extending irrigation systems to other regions, particularly outside of Java [39].

These significant investments in irrigation were aided by rising worldwide oil prices, which resulted in efforts to boost support for water management in Indonesia. The Government helped to enhance the tertiary irrigation system with substantial financial aid by introducing standard irrigation system designs throughout Indonesia. This included the improvements of existing irrigation systems in Subak by the Bali Irrigation Project in the 1980s, which restricted Subak's autonomy and promoted Subak's reliance on government control [35,52]. With substantial investment in water resource development during this period, Indonesia attained self-sufficiency in rice production in 1984 through a centralistic and systematic rice intensification strategy in all irrigated areas. However, since the 1986 oil shock, public investment in water resource development has gradually declined. This oil shock was one of the most disappointing performances of Indonesia's 32-year-presidency at the time, as the country was unprepared for an external economic shock of this magnitude [53]. Since then, despite investments in irrigation infrastructure, the increase in total irrigated area in 2004 was only half of that of the previous years [39].

In 2005, the Indonesian Government developed a new plan called "Long-term Development Plan 2005–2025 (LTDP)", in which Indonesia stated its focus strategies of development for the next 20 years [38]. This plan was followed by a five-year Medium-term Development Plan (MTDP). The development plans for water management are mainly based on the program for constructing reservoirs and dams to increase the availability of water for irrigation and energy. However, the total rice harvested area and the total area under irrigation have not changed much in the last two decades.

3.2. Irrigation Community and Policy Reforms in Indonesia's Irrigation Systems

The concept of the irrigation community started at the beginning of the creation of rainfed rice fields and, subsequently, the discovery of technology to divert water from rivers for irrigation. An irrigation community refers to a group of farmers who use an irrigation system's water supply, also known as farmer water user associations (WUAs) [54]. Subak irrigation in Bali is one example of communal irrigation that was thought to have existed since the end of the first millennium [35,37]. Although the water diversion technique used free intake flows, these discoveries show community involvement, such as labor division, to ensure that the performance of irrigation systems continued indefinitely and sustainably [42].

There was a phase of cohabitation between the irrigation community and the governmental irrigation agencies between 1848 and 1970 [52]. Despite the fact that the Dutch colonials in Indonesia constructed large-scale irrigation systems in the rice fields, local communities made their own improvements and developed irrigation infrastructure, especially at the tertiary level of the irrigation system. Because some of the irrigation infrastructure built by the communities were short-lived and easily damaged when flooded, these irrigation infrastructures were sometimes seen as unregulated [42]. The Subak irrigation system in Bali and the irrigation systems created in the Solo and Yogyakarta districts were mainly regarded as good, as they were built by Dutch specialists [40,55,56].

The welfare politics of the previous generations persisted until Indonesia gained its independence from Japan in 1945. The phrase "*pengairan*", refers to water intake for a general purpose, but was frequently used interchangeably with irrigation. It was officially used in the Indonesian constitution about *Pengairan* No. 11/1974, which regulated water resources. This constitution was constructed to replace the 1936 *Algemeen Water Reglement*, which was deemed insufficient in supporting developmental demands. The constitution was then followed by Government Regulation No. 23/1982 which specifically regulated irrigation water in Indonesia. Another significant endeavor at the time was the formation of the water user association (WUA) in the repaired tertiary unit, although WUAs supporting the tertiary irrigation system was not new [52].

In fostering the WUA, the Government issued Presidential Instruction No. 2 of 1984, which provides direction to all relevant agencies for guiding farmer organizations in using the existing irrigation water [42]. The central Government began to formulate a strategy for WUA to help manage the irrigation network that had already been built. The irrigation and water resource management reform phase were typically consistent with decentralization and regional autonomy. This phase was preceded by Presidential Decree No. 3/1999 and Government Regulation No. 77/2001 addressing irrigation, which basically gave the WUA the authority to oversee irrigation systems. There was a conflict of interest in this phase, for example, between continuing irrigation reform, which emphasized efforts to empower farmers through granting greater management authority, and the interest of maintaining the management framework running through an investment approach, as well as allowing opportunities for the private sector in managing water resources [57].

In 2004, the constitution was changed to implement the Water Resource Act No. 7/2004, pulling back the reform movement by making management transfer optional. The enactment of Water Resource Act No. 7/2004 corresponded with the implementation of the regional autonomy policy (Law No. 32/2004). This constitution allowed the central, provincial, and regional governments to manage and develop the irrigation system based on the type of irrigation system. It also provided share authority between the government (for primary and secondary irrigation systems) and the WUA (for tertiary irrigation systems). In this constitution, irrigation systems were generally organized into the following three layers [57]: (1) the central government responsible for the international irrigation systems (trans-national boundary irrigation systems), cross-province irrigation systems, national strategic irrigation systems, and irrigation systems with an area > 3000 ha; (2) the provincial government responsible for cross-regency irrigation systems and irrigation systems with an area 1000 to 3000 ha; (3) regency government responsible for irrigation systems with an area less than 1000 ha.

At least three factors triggered the enactment of Water Resource Act No. 7/2004, namely efforts to recover from the economic crisis after experiencing political shocks, World Bank-proposed efforts to improve the economy, and global pressure to adopt an integrated and sustainable approach. However, no formal service agreements outline the roles, duties, rights, and obligations of the service provider and the service recipient. In the absence of these agreements, providing services to farmers becomes unreliable [5]. According to the regional autonomy policy, the regencies and provinces have their autonomy and are not subject to national authority. The autonomy policy with the lack of integrated coordination between regions resulted in diverse water resource and irrigation management policies, since each regency or province may have its own policy, governmental institution, personnel structure, financing, and so forth [42]. In 2008, Indonesia released President Decree No. 12/2008, constructing the Water Resources Council (*Dewan Sumber Daya Air*) to coordinate water resources at the regional, provincial, and national levels.

Currently, Indonesia is shifting to a government-supported irrigation system. In the new constitution of Water Resource Act No. 17/2019, the development and management of the irrigation system falls under the Central Government's authority as one united system [57]. Despite the complexity of irrigation management, the new water law has provided a legal foundation for integrated water resource management (IWRM) to be practiced in a river regime unit (RRU), consisting of a single river basin or several interconnected river basins. The new law also acknowledged the role of multi-stakeholders in the decision-making process in water governance. In 2022, Indonesia released President Decree No. 53/2022, in which the new Water Resources Council was established to provide suggestions and technical judgments for the Central Government to further achieve the objectives of Indonesia's water resource management, including irrigation.

4. Challenges to the Indonesia Irrigation System

4.1. Dynamics of Rice Production in Indonesia

According to Boomgard [58], maize supplied a carbohydrate source for people in the Eastern areas of Indonesia in the 17th century. Other food sources, such as cassava (*Manihot utilisima*), sweet potato (*Ipomoea batatas*), and taro (*Colocasia esculenta*), were introduced by Europeans between the 16th and 19th centuries [59]. However, rice (*Oryza sativa*) has become the main diet for practically all Indonesians. Even during the worst of Indonesia's economic turbulence, from 1997 to 1999, other sources of carbohydrates were less popular than rice among most Indonesians [60]. Long-term government policy on subsidies to enhance rice production may help to increase rice consumption's appeal over other foods [14].

With the development of irrigation and the introduction of green technologies, rice production in Indonesia gradually increased over the years. Panuju et al. [14] reported a significant relationship between production and irrigated area in Indonesia from 1961 to 2009, with a coefficient of determination of 0.99. In the last 75 years since the independence of Indonesia, rice productivity has increased three times, primarily due to the area equipped with irrigation systems, which doubled (Figure 3). However, the increment in rice production has hardly been seen for the last decade, with a downward trend seen from 2010. On the other hand, the irrigated area remains constant. According to data from the MoPWH, the total damage to irrigation networks in Indonesia increased by more than 50% between 2010 and 2014. Despite the fact that irrigation facility repair continues, it has not been effective in stopping the damage rate. Most irrigation systems are damaged primarily due to their old age and are poorly maintained, leading to ineffective water intake and delivery systems. The damages include cracks and leaks from the concrete open channels throughout the primary to tertiary irrigation channels, erosion, broken weirs, and inadequate water intake facilities [61,62].

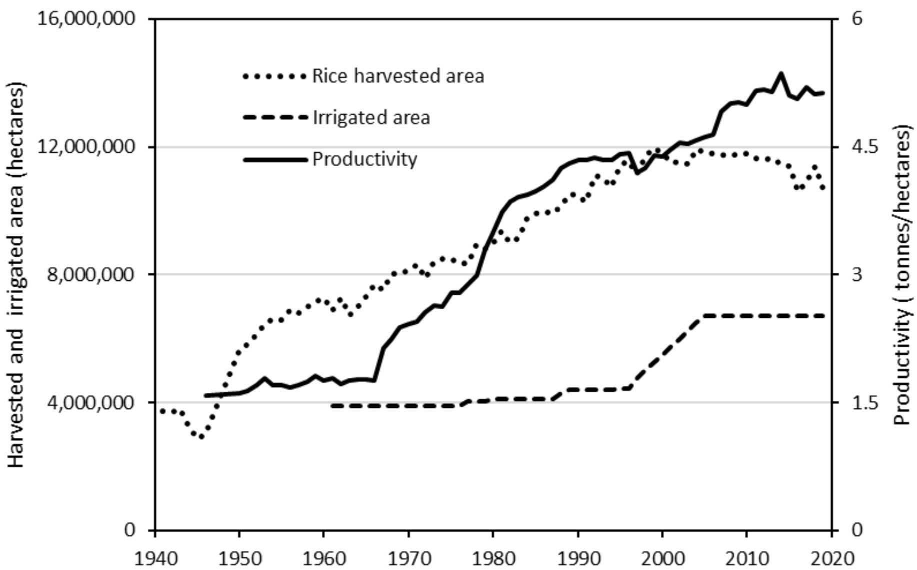

Figure 3. Harvested area, irrigated area, and rice productivity in Indonesia from 1940 to 2020 (Data collected and modified from www.fao.org, www.bps.go.id access, www.litbang.pertanian.go.id, and www.irri.org accessed 15 April 2022).

Aside from the possible ineffective water delivery through the irrigation channels, other factors include increased competition with other sectors and changes in land-use patterns, affecting recent trends. Regardless of the importance of rice production for Indonesia, massive land modification is taking place, especially on Java Island. Specific reports on land-use changes were reported to take place for regions that have been known as the most productive areas, such as Western Java [63], the Northern Coastal Region [64], and North Sumatera [65]. Socioeconomics, urbanization, industrialization, demographics, and policy changes are influential variables. Thousands of hectares of irrigated and valuable agricultural areas in Indonesia have been transferred to other purposes, and the alterations have been mostly unregulated [65]. Between 1981 and 1999, even though Indonesia's government intensively expanded the paddy field area on several islands, nearly 30% (480,000 hectares) of Java's existing rice land was transformed. The collected data from the FAO also showed that the total harvested area of rice in Indonesia declined at the rate of 114.3 thousand hectares per year (Figure 3). Such fast changes in land-use from agricultural land to other uses also suggest that improved paddy rice mapping and monitoring methodologies are critical to developing reliable rice production and irrigation area data [66].

The population of Indonesia is increasing rapidly, with a rate of 3.16 million people per year (Figure 4). The population of Indonesia was 87.7 million in 1960 and 273.5 million in 2020, an almost 200 million difference in 50 years. This increment is faster than the increase in rice production, with a rate of only 0.82 tons per year. Many studies have predicted that the world will face food shortages as the demand increases. For instance, the International Rice Research Institute evaluated the food crisis related to the global population and forecasted that 800 million tons of rice would be needed in 2025 [67]. The Center of Indonesian Policy Studies reported that Indonesia has one of the world's highest rice consumption rates, with 29.13 million tons consumed in 2017 [68]. In accordance with population growth, this quantity is predicted to rise to 31.7 million tons by 2045. In contrast to this rise, rice production in Indonesia has decreased in recent years, indicating that there might be a possibility of an increase in imported rice to Indonesia.

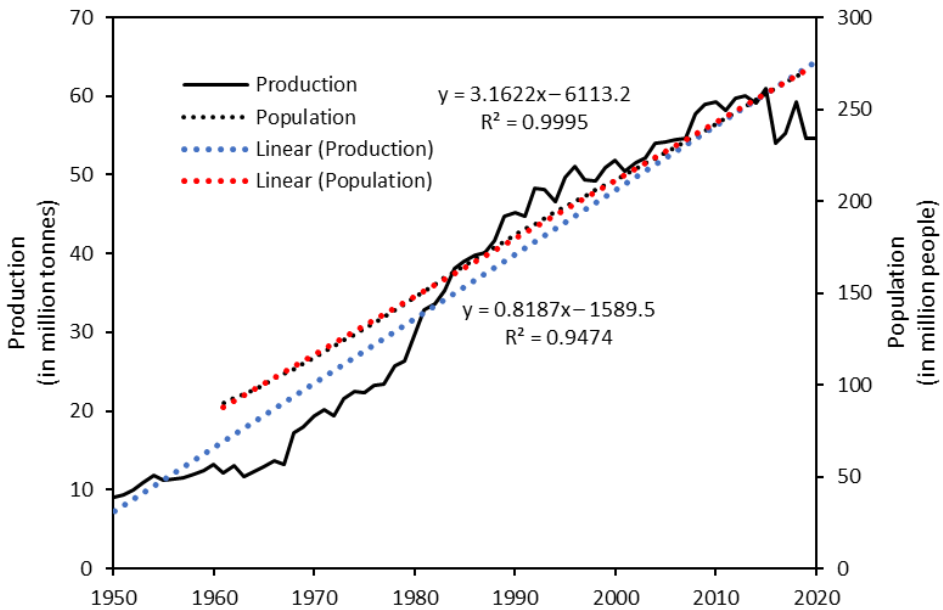

Figure 4. Rice production and population increase in Indonesia (Data collected from www.fao.org, www.bps.go.id accessed 15 April 2022).

4.2. Contribution of Rice Production to Green House Gas (GHG) Emission

Paddy fields are major sources of global atmospheric greenhouse gas (GHG) emissions, including methane (CH_4) and nitrous oxide (N_2O), but these GHGs have rarely been measured in field conditions [69]. Methane (CH_4) is a GHG that ranks second only to carbon dioxide (CO_2) in volume but is 25 times more potent in terms of global warming potential [70]. Methane from rice fields worldwide generates around 1.5% of total world greenhouse gas emissions and has the potential to rise further [71]. Rice is typically grown in flooded fields known as paddy fields, artificially designed ponding systems whose hydrological processes are significantly impacted by water management practices [72,73]. The flooded condition of paddy fields prevents oxygen diffusion into the soil, creating ideal environmental conditions for the growth of methane-emitting bacteria. The longer the flooding/ponded conditions last, the more methane emitting microorganisms accumulate, contributing to methane emissions from rice fields.

The FAO reported that Asia shares 44% of the total agricultural CH_4 and 88% of total rice cultivation CH_4 worldwide, the biggest of the seven continents. Among the Asian countries, Indonesia is the third-highest methane contributor from rice cultivation, following China and India [12]. This is mainly related to the area of paddy fields in the country. According to Wassman et al. [74], irrigated rice cultivation emits roughly 70–80% of CH_4 from the worldwide rice area, followed by rainfed rice (15%). Irrigated rice cultivation ensures rice production all year around, even in the dry season. On the other hand, rainfed rice only allows farmers to cultivate rice during the rainy season, leading to a 50% lower annual rice yield [75].

In Indonesia, rice cultivation has been practiced for millennia using the paddy fields technique (*sawah*) [76]. Centuries ago, each paddy was planted once a year in ponded conditions to produce rice without chemical fertilizer. This long history of rice cultivation has made the paddy approach become a part of Indonesian belief and culture [77,78]. The availability of free water and irrigation infrastructure has also made it easy for Indonesian farmers to get access to water. Farmers also found that the flooding technique helps weed control in paddy fields with relatively less work to manage paddy production during the season, thus, allowing them to also work at a side job to supplement their incomes [79,80].

Figure 5 illustrates the CH_4 emission from rice-growing fields compared to other landscape sources in Indonesia. The average annual CH_4 emission from rice cultivation in Indonesia is 2115.5 kilotons. It is two to three times higher compared to manure management systems and gas emissions from forest fires. As a result, irrigated rice is one of the most significant potential targets for agricultural GHG mitigation measures. Methane emissions can be reduced by a well-planned agricultural strategy that minimizes or reduces the time of flooding in paddy fields. The sharp rise in CH_4 emissions from forest fires was seen from August 1997 to June 1998 due to a series of forest fires at the time. These forest fires were recorded as one of Indonesia's most devastating forest fires, resulting in haze and smoke covering the Southeast Asia region [81,82].

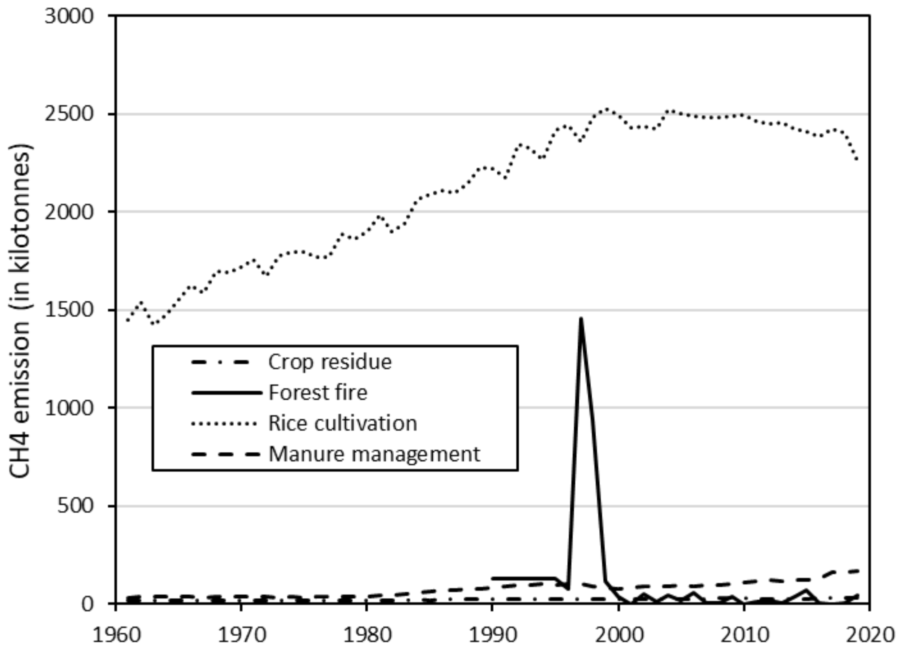

Figure 5. Methane emission from Indonesia (Data collected from www.fao.org accessed 15 April 2022).

In addition to CH_4, paddy fields also hold a threat in terms of the release of N_2O. In a 100-year time horizon, N_2O has a 296-fold greater global warming potential than CO_2 [83], 10 times higher than that reported for CH_4 [84]. It generally assumes that the paddy field emits a small amount of N_2O under the highly anaerobic conditions of paddy soils, as N_2O would be reduced to nitrogen (N_2). However, it is well-known that N-fertilizer usage and the continuous cycle of the anaerobic–aerobic phase promote denitrification with N_2O gas as a product [85,86]. Recent studies reported that rice season and rotation emit a substantial amount of N_2O [87,88]. Irrigation management options, such as intermittent irrigation, might also have conflicting effects on paddy field contribution to the greenhouse effect. There would be an exchange between the decrement in CH_4 and the increment in N_2O. In order to reduce GHG emissions and lessen the contribution of rice fields to the greenhouse effect, it is crucial to evaluate the integrated impacts of water management and fertilizer application [89], as well as to conduct a concurrent measurement of both gasses in various paddy field conditions [84].

The main parameters governing N_2O and CH_4 emissions during paddy rice production are water management and nitrogen fertilizer application rate [90]. It is well known that to double the food output to meet the food demand for the world's rising population, the worldwide demand for N fertilizer is expected to triple by 2050 [88]. Akiyama et al. [91] reported that N_2O emissions from paddy fields with continuous flood irrigation were calculated to be 341 g N ha^{-1} $season^{-1}$ and 993 g N ha^{-1} $season^{-1}$ for areas with mid-season drainage. Mid-season drainage allowed the paddy field to dry out and be left without surface water for seven days prior to tillering [92], thus reduce the period of ponding. Upland rice fields, which are not flooded and, hence, do not emit considerable amounts of CH_4 and N_2O, account for around 10% of global rice output and 15% of the global rice area under cultivation [93]. In Indonesia, only 11% (1.16 million ha) of the total rice area is considered upland rice [93], even though there is a potential to bring 5.27 million ha of dryland area under rice production in Indonesia [94].

4.3. Threat of Climate Change to Rice Production and Irrigation System in Indonesia

Indeed, climate change brings potential future risks to rice production in Indonesia, necessitating adaptation of better scientific techniques, such as the use of micro-irrigation and biotechnology [95]. Global climate change affects temperature and rainfall, which eventually influences the water availability in the rivers during Indonesia's wet and dry seasons [96]. Figure 6 shows the variations in temperature and precipitation in Indonesia from 1901 to 2020. Even though there is no explicit down or upward trend in total annual rainfall, there have been bigger gaps between dry and wet years since the 1970s, and the occasional occurrence of extreme storm events. The standard deviation of annual rainfall from 1970 to 2020 is 225.4 mm, which is100mm higher than the previous periods. These concerns have increased the significance of upgrading the irrigation systems to improve water management efficiency and reduce GHG emissions from paddy fields.

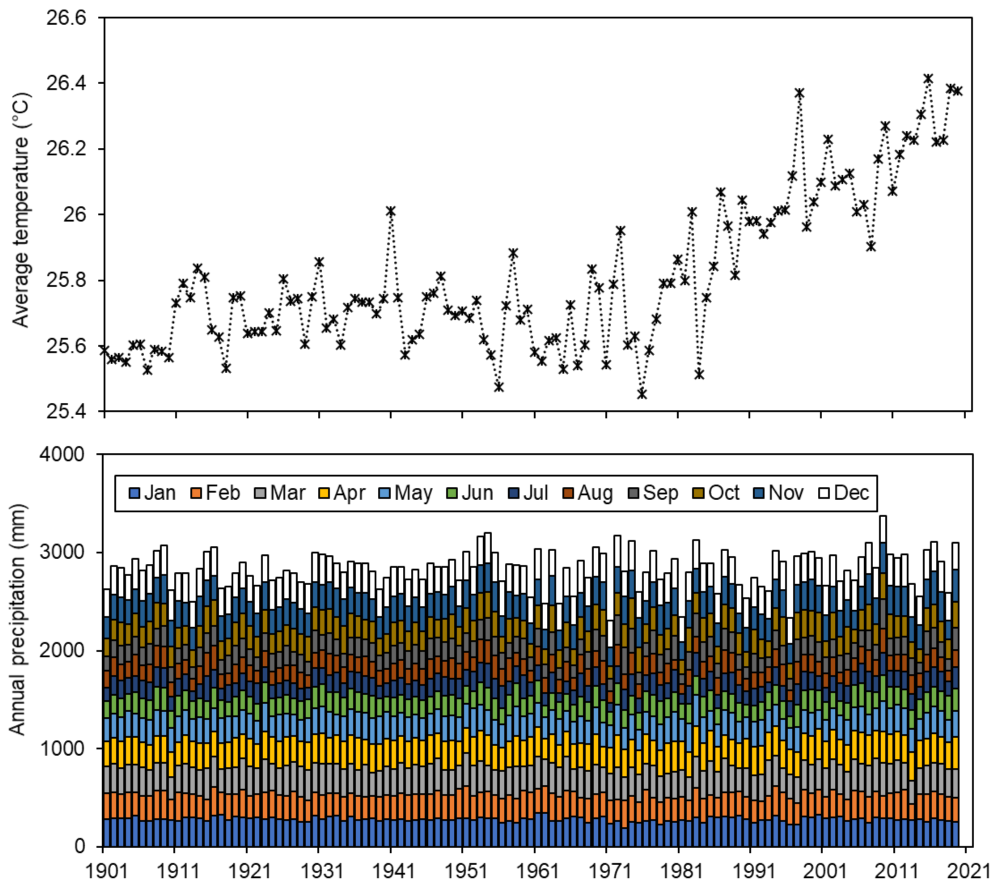

Figure 6. Dynamics of precipitation and the average temperature in Indonesia from 1901–2019 (Data collected from World Bank Climate Change Knowledge Portal www.climateknowledgeportal.worldbank.org accessed 25 April 2022).

The rise in temperature in Indonesia is obvious from 1970 to 2020 and, thus, raises concerns about water losses by evaporations and the increased amount of microbes producing CH_4. Soil temperature is recognized to be an essential factor in influencing soil microbial activity [93]. Temperature increases will also affect several of the factors that drive anaerobic CH_4 generation from soil water and the organic matter (soil biomass). Yamane and Sato [97] discovered that CH_4 formation peaked at 35 °C in wet soils and slowed down in temperatures under 20 °C. Seeing the consistent temperature increase over the previous 30 years at a rate of 0.14 °C per year, Indonesia might pose a significant threat by contributing to the world's GHG emissions from paddy fields if considerable mitigation measures are not developed and implemented at the farm level.

5. Proposed Solutions for the Future Irrigation System in Indonesia

5.1. Irrigation Modernization in Indonesia

In 2015, the MoPWH released a regulation on the operation and maintenance of irrigations in Ministerial Regulation No. 12/PRT/M/2015. Although the OM regulation was released seven years ago, it has failed to reduce the amount of damaged irrigation infrastructure. This Ministerial Regulation, regarded as conventional, essentially controls the operation and maintenance of irrigation in general [98]. Due to insufficient maintenance, fast degradation, and loss of productivity of irrigation systems, worsened by other complicated factors, such as a significant increase in population and a decrease in the total irrigated and agricultural area, Indonesia has been struggling to achieve self-sufficiency in rice production [99].

The 2019 Circular Letter (*Surat Edaran*) by the Director General of Water Resources MoPWH No. 1/SE/D/2019 has become the latest guidance for Indonesia's Irrigation Modernization. This Circular Letter issues guidance on irrigation modernization. It aims to achieve an oriented participatory irrigation management system on the fulfillment of irrigation effectively, efficiently, and sustainably promoting food and water security by improving water supply, infrastructure, irrigation management, institution managers, and human resources. Strategies for increasing irrigation systems' efficiency and performance through irrigation modernization include the following: (a) the construction of highly efficient new irrigation networks; (b) the rehabilitation of existing irrigation networks; (c) increasing the capacity of irrigation institutions; (d) increasing the effectiveness of irrigation water allocation methods; and (e) use of sub-optimal lands through swamp revitalization. Apart from this Circular Letter, Indonesia seems reluctant to invest more in building a robust legal foundation as there is not yet a new ministerial regulation governing irrigation modernization.

Based on MTDP 2020–2024, Indonesia will increase the percentage of premium irrigation from 12.3% in 2019 to 16.4% by 2024 [38]. However, this government plan neglects to put forward the OM challenges and issues for the existing irrigation system. The challenges in irrigation modernization include the possible increase in population, food demands, global warming effects, and a lack of institutional and human resource support. These issues shall be utilized as input in the operation and maintenance (OM) execution. Emerging environmental factors, such as climate change that strains land and water resources, make the country more vulnerable to water-related threats, such as flooding during the wet season and water shortage during the dry season. The occurrence of water shortage over wide areas also worsens the use competition of irrigation management. With the threat of climate change, farm-level adaptation measures, such as improved irrigation scheduling, crop rotation changes, new crop varieties, and improved irrigation efficiency, appear to contribute significantly to the farmer's adaptation of better practices that mitigate climate change [100].

Considering how recent rainfall in Indonesia can be very dynamic, the operation of the irrigation system should be no longer static. Instead, it should be carried out in a flexible manner. One endeavor to attain flexible management is forming an irrigation management institution and human resources capable of flexibly changing the execution of irrigation management so that the agricultural community can be appropriately serviced. The capacity to regulate water effectively enough to ensure both soaking and drying is significantly important. To mitigate CH_4 emission, Indonesia might need to consider adapting irrigation schedules and aerobic irrigation systems that reduce ponding duration in the rice field [101–103]. This approach has been applied in several countries, and has been proved to save water and reduce methane emissions [104]. Chinese and Japanese farmers generally drain their rice paddies once throughout the growing season because they have discovered that it boosts yields, and scientific studies have revealed production benefits everywhere in the world [84,89]. According to Sass et al. [105], a single mid-season drain lowered seasonal CH_4 emission rates by 50% (from 9.27 g/m^2 to 4.86 g/m^2). Although there is still an ongoing debate on its contribution to N_2O emission, a shorter flooding duration or intermittent irrigation also saves irrigation water, since less water percolates through the ground, runs off, or evaporates [104]. Additionally, these water management approaches possibly solidify Indonesia's national climate commitments, as part of the Paris Agreement, to decrease GHG emissions by 29% in 2030 [106].

5.2. Improve Communities' Involvement in Tackling Irrigation and Climate Change Issues through Incentive-Based Policies

Farmers and WUAs are at the frontline of making the irrigation system efficient. However, farmers generally have less education and insufficient incomes to adopt better technologies. There is an urgent pressure to apply irrigation modernization that fits the current challenges that have become very dynamic. However, farmers hardly coped with the changes in technology and water usage because of a lack of education and disposable incomes. Moreover, farmers gained minimum advantages from following irrigation modernization. The incentive program is expected to increase WUAs' participation in irrigation services and OM. The major benefits of these initiatives were improved OM and cost savings in OM, rehabilitation, and upgrading. The key issues include how to achieve higher quality maintenance by having farmers contribute more significantly to the cost of management, restoration, and upgrading by utilizing government money in ways that encourage local investment [99]. Qureshi et al. [107] reported that the policy of reimbursing irrigators and water delivery companies to improve on-farm irrigation and water conveyance shows a more significant return than centralizing the water market by the Government. Alas, this incentive program should be followed by genuine guidance, regular training, and capacity building to ensure the achievement of irrigation services and farmers' welfare. Furthermore, WUA empowerment is required and critical in order to achieve more equitable irrigation water allocation [108].

Regarding methane reduction, farmers are not rewarded for lowering emissions nor penalized for increasing methane. Farmers should be given cash incentives for reducing GHG emissions for adopting better irrigation and agricultural practices. Although entire agricultural districts may profit from reducing flood irrigation practices and preserving water, individual farmers frequently have little motivation to do so because they receive free water. It is also part of their belief that a paddy should be ponded since it is an inherited planting system of their ancestors [109]. Moreover, farmers' reliability in irrigation scheduling is low. Frequent water unavailability, uneven water distribution, and discontent with the punctuality of irrigation water have been sources of conflict and inefficient production systems [110].

Despite the potential benefits of better water management, such possibilities will mostly be lost unless governments introduce incentive-based policies and encourage the farmers to dive into the new technical specifics farm by farm [111]. The Chinese Government pushed institutional improvements in water management and offered economic incentives to conserve water. Wang et al. [112] reported that only institutions that introduced water-saving incentives were successful in making irrigation practices effective and efficient. Because reducing agricultural GHG emissions and increasing the farmers' welfare has been a low priority for governments, even minimal resources have not been invested [104].

5.3. Strengthen Local Institutions and Communities Support for Irrigation

Looking at Indonesian history in irrigation, which is estimated to have existed for thousand years, it can be said that there is a close interdependent relationship between the irrigation system and the socio-cultural history of Indonesians. Water resources and all elements of their utilization are common-pool resources and polycentric, based on the features of the resources [113]. As a result, Indonesians believe in the free intake of water resources without contributing to its sustainability and, thus, are prone to overexploitation of water [114]. Human–water system interactions are also heavily mediated by relatively intangible ideas, such as community norms and behaviors [109,115]. It is typical for an Indonesian to believe that rice requires a lot of water. *Sawah*, or rice fields with ponds, is an ancient method used to store water during the rainy season, and the Indonesian ancestors used paddy as a crop in this ponded field. As it has occurred for a long time, many farmers incorrectly regarded rice as an aquatic crop.

With the increased future threats, an integrated approach to understanding the evolving linkages between water and society is crucial for current and continuing studies [116]. According to Arif et al. [117] successful irrigation system management in Indonesia is dependent on the following: (i) legal principles and clear management objectives; (ii) strong underlying capital (assets) including water, human resources and institutions, and technology; and (iii) a dependable management system capable of realizing the management objectives. Therefore, Indonesian irrigation modernization will not be successful without continuous support, research, and development that involves the participation of multi-stakeholders, including WUAs and the Indonesian population. However, the current Indonesian Constitution about Water Resource Act No. 17/2019, which rules out the idea of the irrigation system as one united system, where all management authority is integrated under the Central Government, might hinder the involvement of local Government, institutions, and WUAs. It is long known that decentralization has been promoted as a preferred method to increase the efficiency of government irrigation spending [118] and to acquire support from local institutions [119].

5.4. Biotechnology, Upland Rice Field, and Improved Research

Another essential factor in alleviating rice production in Indonesia and reducing water ponding in rice fields is the type of paddy varieties used by Indonesian farmers. Since 1905, Indonesia has had a seed research facility at Bogor. Indonesia has been conducting research on upland rice varieties that need less water, called *gogo* varieties. The most prolific inventions for seed varieties happened between 1981 and 1985 and 2001 and 2005, during the 5-year development programs. Between 2001 and 2005, the institutions developed 31 *sawah* (lowland varieties) and 5 *gogo* (upland varieties) [14], with the primary goal of meeting particular needs, such as pest resistance, microclimate adaptability, good flavor, and increased yield. The main distinction between *sawah* and *gogo* cultivars is their yield potential. *Sawah* types can yield between 5.5 and 8.0 tons per hectare, whereas *gogo* cultivars can generate up to 5 tons per hectare [14]. It is known that upland paddy varieties are 53.5% less profitable than lowland varieties, making farmers reluctant to shift to upland rice cultivation techniques [120], but upland rice production systems will have reduced GHG emissions, for which farmers should be given economic benefits to compensate for the loss from reduced rice yields in upland systems.

To achieve sustainable rice production in Indonesia, integrated hydrology, biotechnology, and socio-cultural research are needed. Indonesia urgently needs continued innovation and improved technology to tackle the sustainable irrigation challenges, in which several institutions, such as universities and governmental research institutes, should get involved and collaborate with other international centers of excellence, such as the International Rice Research Institute in Manila, the Philippines. With the growing pressure from global communities, limited agricultural land, and the threats of climate change, Indonesia, with obvious potential as a leading agrarian country, has no reason not to give the agricultural sector the main spotlight for Indonesia's development.

6. Conclusions

Indonesia, an archipelago country, has a long history of irrigation development which is estimated to have existed for thousands of years. Indonesia is one of the few countries in the world blessed with the most abundant water resources but is not free from the water crisis because of water mismanagement and/or inefficient irrigation systems. Most fresh water in Indonesia is allocated for irrigation in the agricultural sector, which contributes to 13.7% of the Indonesian GDP, placing irrigation as one of the most strategic measures to help reduce GHG emissions and water savings. Indonesia's irrigation systems have undergone several regulatory reforms that mostly ruled the decentralization or centralization of irrigation management. Threats, such as climate change, increased population, and food and water security, are motivating Indonesia to upgrade its irrigation and food systems. Indonesia has shown a downward trend in rice production in the last two decades amid possible inefficient water delivery and water use at the farm level, making Indonesia a rice-importing country once again. Irrigation modernization in an integrated manner requires active participation among different stakeholders, such as the Government, farmers, water user associations (WUAs), and local research institutions. Incentive-based policies need to be developed to increase WUA and farmers' participation in the management of irrigation systems. Furthermore, research institutions need to be strengthened to develop new science and technologies in irrigation, biotechnology, and socio-hydrology should be implemented to boost rice production in the coming years, and to convince farmers to reduce water consumption and use practices to mitigate climate change in rice production systems.

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