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SUBOPTIMAL LAND MANAGEMENT TO INCREASE RICE PRODUCTIVITY

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Abstract

Suboptimal land is a strategic resource with great potential to support increased rice production in Indonesia amidst the increasingly limited area of productive rice fields due to land conversion, environmental degradation, and the pressures of climate change. This land includes acidic drylands (Ultisols and Oxisols), tidal swamps, lowlands, peatlands, saline lands, and other marginal lands that face various constraints, such as high acidity levels, low soil fertility, aluminum (Al) and iron (Fe) poisoning, salinity, and limited water availability. Various research results published in accredited national journals and reputable international journals show that rice productivity on suboptimal land can be increased through the implementation of integrated land management. These strategies include the use of ameliorants such as lime, dolomite, biochar, and gypsum to improve soil chemical properties, the addition of organic matter to improve the physical and biological quality of the soil, the application of balanced fertilization based on location specific, the use of rice varieties adaptive to environmental stress, efficient water management, and the use of biofertilizers *and* functional microorganisms to increase nutrient uptake efficiency. In addition, the development of sensor-based precision agriculture technology, *the Internet of Things* (IoT), remote sensing, drones, and artificial intelligence (*AI*) opens up new opportunities for more effective and sustainable land management. This review article aims to synthesize the results of recent research on suboptimal land management to increase rice productivity, identify research gaps , and formulate directions for the development of technology that is adaptive to climate change. The results of the study indicate that the application of integrated management technology can increase rice productivity, improve soil quality, increase input efficiency, and support the creation of a sustainable and climate-resilient rice production system.

Keywords: suboptimal land, rice productivity, soil amelioration, biofertilizer, precision agriculture, climate change.

Introduction

Rice (*Oryza sativa* L.) is a strategic food commodity that plays a crucial role in maintaining national food security, as it remains the staple food for the majority of Indonesia's population. With population growth, urbanization, and changes in consumption patterns, national rice demand continues to rise annually. However, efforts to increase rice production face increasingly complex challenges due to the reduction in productive rice fields due to land conversion for residential, industrial, and infrastructure development. This situation is exacerbated by soil degradation and the impacts of climate change, which impact the stability of rice production. Therefore, developing suboptimal land is a strategic alternative to sustainably maintain and even increase national rice production (Mulyani et al., 2021; FAO, 2023).

Indonesia has a very large potential for suboptimal land, estimated at more than 90 million hectares spread across Sumatra, Kalimantan, Sulawesi, Papua, and parts of Java. Suboptimal land includes Ultisol, Oxisol, tidal swamps, lowland swamps, peatlands, saline soils, and marginal drylands that have various limiting factors for plant growth. These limiting factors include high levels of soil acidity, low organic matter content, macro and micro nutrient deficiencies, aluminum (Al) and iron (Fe) poisoning, salinity, and limited water availability. Nevertheless, various research results show that these lands still have great potential to be developed as rice production centers if managed with appropriate technology and in accordance with the characteristics of each agro-ecosystem (Mulyani & Sarwani, 2013; Ritung et al., 2015).

Climate change is another factor increasing the complexity of suboptimal land management. Rising air temperatures, changing rainfall patterns, the increasing frequency of floods and droughts, and changes in the dynamics of plant pests have all impacted rice productivity in various regions. On suboptimal land, these impacts tend to be greater due to soil conditions that naturally have physical, chemical, and biological limitations. Research published in international journals shows that an average temperature increase of 1–2°C can accelerate the reproductive phase of rice plants, shorten the grain filling period, and reduce yields. While changes in rainfall patterns increase uncertainty about planting times and the risk of crop failure (IPCC, 2023; Zhao et al., 2017). Therefore, land management strategies are needed that can increase productivity while strengthening the adaptive capacity of rice cultivation systems to climate change. Various technological innovations have been developed to address the challenges of suboptimal land management, including soil amelioration using lime, dolomite, biochar, and organic matter; site-specific balanced fertilization; the use of rice varieties adaptive to environmental stress; efficient water management; the use of biofertilizers *;* and the application of sensor-based precision agriculture, *the Internet of Things* (IoT), remote sensing, and artificial intelligence . Several studies published in SINTA-accredited national journals and reputable international journals like Scopus report that these technological combinations can increase rice productivity, improve soil quality, increase the efficiency of production input use, and support sustainable agricultural development on suboptimal land (Agegnehu et al., 2017; Lal, 2020; Mulyani et al., 2021). Given these conditions, studies on suboptimal land management are crucial for formulating effective strategies to support increased rice productivity and national food security amidst the challenges of climate change.

2. Characteristics of Suboptimal Land

Suboptimal land is agricultural land with one or more limiting factors, resulting in relatively lower productivity compared to optimal irrigated rice fields. According to Mulyani and Sarwani (2013), suboptimal land in Indonesia includes acidic drylands (Ultisols and Oxisols), tidal swamps, lowland swamps, peatlands, saline soils, and marginal drylands. This land area is estimated to reach more than 90 million hectares and is spread across the islands of Sumatra, Kalimantan, Sulawesi, Papua, and parts of Java. Despite its limitations, this land holds significant potential as a source of rice cultivation expansion if managed with appropriate technology. Therefore, understanding the physical, chemical, and biological characteristics of the land is fundamental to determining appropriate management strategies (Mulyani et al., 2021).

One of the main obstacles in most suboptimal land is **the level of soil acidity (low pH)** . Ultisol and Oxisol soils generally have a pH ranging from 3.5–5.5, resulting in low availability of essential nutrients such as phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K). Under these conditions, nutrients are easily fixed and thus unavailable to plants. In addition, soil acidity also reduces the activity of microorganisms that play a role in the decomposition of organic matter and nutrient mineralization. Research by Fageria and Baligar (2008) explains that increasing soil pH through amelioration is a very important initial step in increasing crop productivity on acidic soils. Similar findings were also reported by Abdurachman et al. (2008), who stated that liming can increase fertilizer efficiency and crop productivity on acidic dry land.

Another characteristic that is a major limitation is **the high content of available aluminum (Al) and iron (Fe)** , especially in acidic soils and swamps. At low pH conditions, Al^{3+} ions become more soluble and are toxic to plant root systems. Aluminum toxicity causes stunted root growth, decreased water and nutrient absorption, and ultimately inhibits rice plant growth. In tidal swamps, reducing conditions increase the solubility of Fe^{2+}, which can cause iron toxicity in rice plants. Common symptoms include browning of leaves, stunted growth, and decreased yields. According to Subiksa et al. (2019), water table management and the application of ameliorants are effective strategies to reduce Fe and Al toxicity in acidic swamps.

In addition to acidity issues, **low organic matter content** is also a key characteristic of suboptimal soils, particularly in Ultisols and Oxisols that have undergone advanced weathering. Low organic matter content leads to decreased cation exchange capacity (CEC), less stable soil structure, low water retention capacity, and limited soil microbial activity. Lal (2020) explains that organic matter is a key indicator of soil health *because* it plays a role in simultaneously improving the physical, chemical, and biological properties of the soil. The addition of compost, manure, and biochar has been shown to increase soil organic carbon content, improve soil aggregation, and enhance the efficiency of nutrient utilization by plants (Agegnehu et al., 2017).

Macro and micro nutrient deficiencies are also common constraints found in suboptimal land. Phosphorus (P) is often fixed by Al and Fe, making it difficult for plants to absorb, while nitrogen (N) is easily lost through leaching and denitrification. Furthermore, micronutrients such as zinc (Zn), copper (Cu), and boron (B) are often present at low concentrations, inhibiting plant growth. Dobermann and Fairhurst (2000) explain that the application of site *-specific nutrient management* can increase fertilizer use efficiency while improving rice productivity. In Indonesia, this approach has also been widely recommended for various types of suboptimal land because it can adjust nutrient requirements based on soil conditions and plant needs (Mulyani et al., 2021).

In some coastal areas, **soil salinity** is becoming an increasingly important limiting factor due to seawater intrusion and the increasing frequency of droughts resulting from climate change. High salt concentrations increase soil osmotic pressure, disrupting root water uptake. Furthermore, the accumulation of sodium ions (Na^+) can disrupt the balance of other nutrients, particularly potassium (K) and calcium (Ca), which play a crucial role in rice plant growth. Munns and Tester (2008) explain that salinity is a major limiting factor for crop production in tropical and subtropical regions. The use of salinity-tolerant varieties, drainage management, and gypsum application are some of the strategies widely recommended to mitigate the negative impact of salinity on rice productivity.

Another important characteristic is **the issue of water management** . In tidal and lowland swamps, plants often experience prolonged inundation during the rainy season, while marginal drylands experience water deficits during the dry season. Fluctuations in water availability cause drastic changes in soil conditions, affecting nutrient availability, microbial activity, and plant growth. Micro-water management, drainage canal construction, and the implementation of an alternating wetting *and drying (AWD*) irrigation system have been shown to increase water use efficiency while reducing greenhouse gas emissions in rice cultivation (Bouman et al., 2007; Setyanto et al., 2020). This strategy is also an important part of *the Climate-Smart Agriculture* concept to increase the resilience of rice production systems to climate change.

Overall, the characteristics of suboptimal land indicate that each type of land has different limiting factors, thus requiring a site - *specific management approach* . The integration of soil amelioration technology, the use of organic matter, balanced fertilization, water management, the use of adaptive varieties, and the use of precision agriculture technology are key to increasing rice productivity sustainably. Various research results from accredited national journals and reputable international journals indicate that the success of suboptimal land management is largely determined by the ability to address physical, chemical, and biological constraints of the soil in an integrated manner, so that previously unproductive land can be optimized as a source of future food production (Mulyani et al., 2021; Lal, 2020).

3. Suboptimal Land Management Strategy to Increase Rice Productivity

Suboptimal land management is a strategic approach to increasing rice productivity amidst the increasingly limited availability of productive paddy fields and the increasing pressures of climate change. Suboptimal lands, such as Ultisols, Oxisols, swamps, peatlands, saline soils, and marginal drylands, have highly diverse characteristics, requiring specific management technologies tailored to the biophysical conditions of each region. Various studies have shown that applying a single technology alone is unable to address all the limiting factors present in these areas. Therefore, the concept of **integrated land management** is the most effective approach because it combines various mutually supportive technological components to improve soil quality, input efficiency, and crop productivity (Mulyani et al., 2021; Lal, 2020). An integrated approach to suboptimal land management includes improving the physical, chemical, and biological properties of the soil through the application of ameliorants, the use of organic matter, site-specific fertilization, the use of adaptive superior varieties, water management, and the application of precision agriculture technologies. Each component has a complementary function in addressing the constraints encountered on marginal land. For example, the application of dolomite or lime aims to increase soil pH and reduce aluminum toxicity, while the application of compost and biochar increases organic carbon content, cation exchange capacity, and the activity of soil microorganisms. At the same time, the use of varieties tolerant to environmental stress can improve the ability of plants to utilize unfavorable land conditions. The synergy between these technologies has proven to be more effective than the application of partial technologies because it can improve land productivity sustainably (Fageria & Baligar, 2008; Agegnehu et al., 2017).

In addition to soil fertility, the success of suboptimal land management is also greatly influenced by water resource management. In swampy areas, a water level control system is required to reduce iron (Fe) and aluminum (Al) toxicity, while in dry areas, water conservation technology is needed to ensure plants maintain adequate moisture throughout the growing season. Good water management not only increases water use efficiency but also improves fertilizer efficiency, increases soil microbial activity, and reduces greenhouse gas emissions. According to Bouman et al. (2007), the application of the **Alternate Wetting and Drying (AWD) system** can save up to 30% on water use without reducing crop yields. Under certain conditions, it can even increase rice productivity while reducing methane emissions. The development of modern agricultural technology is further strengthening the effectiveness of suboptimal land management through the application of **Precision Agriculture** and **Climate-Smart Agriculture concepts** . The use of soil sensors, *the Internet of Things* (IoT), drones, satellite imagery, geographic information systems (GIS), and artificial intelligence (*AI*) enables more accurate land management based on actual field conditions. This technology can be used to monitor soil moisture, nutrient status, and plant growth, as well as predict irrigation and fertilization needs in real time. This results in more efficient use of production inputs, increased productivity, and minimized negative environmental impacts. Various international studies have shown that integrating digital technology with soil and water management is a key direction for future agricultural development, capable of supporting a productive, climate-adaptive, and sustainable rice production system (Lal, 2020; Zhang et al., 2021).

3.1 Soil Amelioration Using Dolomite, Biochar, Compost, and Gypsum

remediation is a crucial initial step in managing suboptimal land, particularly acidic soils, swamps, and saline areas. The primary goal of amelioration is to improve the chemical, physical, and biological properties of the soil, thus improving root conditions for rice plant growth. Various ameliorants have been used, including dolomite, agricultural lime, biochar, compost, manure, and gypsum, applied according to land characteristics (Fageria & Baligar, 2008). Dolomite is the most widely used ameliorant in Ultisol and Oxisol soils because it can increase soil pH while providing calcium (Ca) and magnesium (Mg). Increasing soil pH reduces the solubility of toxic aluminum (Al) and iron (Fe), thereby increasing the availability of phosphorus and other nutrients. Research by Abdurachman et al. (2008) showed that applying dolomite to acidic dryland significantly increased fertilizer efficiency and crop productivity.

In addition to dolomite, **biochar** is increasingly being developed as an ameliorant due to its ability to increase cation exchange capacity (CEC), improve soil structure, enhance water retention, and increase soil organic carbon content. Agegnehu et al. (2017) reported that biochar application can increase crop productivity while reducing greenhouse gas emissions. Biochar also serves as a habitat for soil microorganisms, thus supporting increased soil biological activity. The use of **compost and organic fertilizers** is an important strategy for improving suboptimal soil quality. Adding organic matter can improve soil aggregation, increase microbial activity, enhance water-holding capacity, and improve the efficiency of chemical fertilizer use. Lal (2020) states that increasing soil organic carbon content is a key indicator of soil health *and* the basis for developing sustainable agriculture.

In saline soils, **gypsum ($CaSO_4 \cdot 2H_2O$)** is the main ameliorant that functions to replace sodium ions (Na^+) in the soil adsorption complex with calcium ions (Ca^{2+}), thereby improving soil structure and reducing the negative impact of salinity on plant growth. The combination of gypsum with salt leaching *has* been proven effective in increasing rice productivity in saline soils (Qadir et al., 2014).

3.2 Site-Specific Nutrient Management

Fertilization is a crucial factor in determining rice productivity on suboptimal land. However, fertilizer dosages are often inappropriate for soil conditions, resulting in low fertilizer efficiency. Therefore, the concept of **Site-Specific Nutrient Management (SSNM)** was developed to adjust the type, dosage, timing, and method of fertilizer application based on plant needs and soil characteristics. Dobermann and Fairhurst (2000) explained that SSNM can increase the efficiency of nitrogen, phosphorus, and potassium use, thereby increasing crop yields without excessive fertilizer use. In Indonesia, this technology has been adopted through the use of **the Paddy Soil Testing Kit (PUTS)** and **the Nutrient Expert application** , which helps farmers determine fertilizer dosages based on specific land conditions (Mulyani et al., 2021). In addition to increasing yields, SSNM can also reduce nutrient loss through leaching and volatilization, making it more environmentally friendly.

3.3 Use of Tolerant Rice Varieties on Suboptimal Land

Variety selection is a key component in suboptimal land management because it determines the plant's ability to adapt to various environmental stresses. Suboptimal land generally has limiting factors such as soil acidity, aluminum (Al) and iron (Fe) toxicity, salinity, waterlogging, and drought, which can inhibit growth and reduce rice yields.

Therefore, using varieties tolerant to abiotic stresses is a more efficient strategy than relying solely on improving land conditions through external inputs. According to Mulyani et al. (2021), the use of adaptive varieties is a priority technology for optimizing suboptimal land use in Indonesia because it can increase productivity while reducing the risk of crop failure. Plant breeding programs in Indonesia have produced a variety of new superior varieties specifically designed for various suboptimal agro-ecosystem conditions. In tidal and lowland swamps, the Agricultural Instrument Standardization Agency (BSIP) has developed a group of **Inpara (Swamp Rice Inbred) varieties** that are adaptable to flooding, iron toxicity, and water level fluctuations. Several varieties, such as **Inpara 2, Inpara 3, Inpara 8, and Inpara 10,** are reported to have higher productivity than local varieties and can produce more than 5–7 tons of dry grain per hectare under good management conditions (BB Padi, 2022). These advantages make the Inpara variety one of the main recommendations for rice development in Indonesia's swamplands.

For acidic drylands, the government has developed **the Inpago (Gogo Rice Inbred) series** , which is tolerant of drought, acidic soil, and low fertility. Varieties such as **Inpago 8, Inpago 10, and Inpago 12 demonstrate adaptability to Ultisol and Oxisol soils, maintaining relatively stable productivity despite limited water availability. Furthermore, various Inpari** varieties have been developed for both irrigated and rainfed rice fields, tolerant to specific environmental stresses, such as flooding, drought, and pest and disease attacks. These varieties provide farmers with flexibility in selecting varieties suited to their land characteristics and local climate conditions (Mulyani et al., 2021).

Physiologically, tolerant varieties have better adaptation mechanisms than conventional varieties. In acidic soil conditions, some varieties are able to limit the absorption of aluminum ions into the root tissue, thus maintaining proper root system growth. In areas experiencing iron toxicity, tolerant varieties are able to oxidize Fe^{2+} ions around the rhizosphere, thereby reducing iron accumulation in plant tissues. Meanwhile, in saline conditions, plants are able to maintain the balance of sodium (Na^{+}) and potassium (K^{+}) ions through cell membrane selectivity mechanisms, so that photosynthesis and biomass formation continue to occur optimally (Munns & Tester, 2008).

Climate change further emphasizes the importance of using adaptive varieties in rice cultivation systems. Rising temperatures, changing rainfall patterns, and the increasing frequency of floods and droughts cause plants to face more complex stresses than before. Zhao et al. (2017) reported that rising global temperatures have the potential to reduce rice yields due to disruptions in flowering and grain filling. Therefore, developing varieties tolerant to high temperatures, drought, waterlogging, and salinity has become a priority in plant breeding programs in various countries.

In addition to increasing resilience to environmental stress, the use of adaptive superior varieties also offers advantages in terms of efficient use of production inputs. Varieties with better root systems are able to absorb water and nutrients more efficiently, thereby reducing fertilizer requirements. Some varieties also have earlier harvest times, which can increase the cropping index and reduce the risk of crop failure due to seasonal changes. According to Ismail et al. (2013), integrating tolerant varieties with soil and water management technologies can produce greater productivity increases than applying either technology alone.

Thus, the use of tolerant varieties is an integral component of suboptimal land management strategies. Successful rice cultivation on marginal land is strongly influenced by the suitability of variety characteristics to growing conditions. Therefore, the development and dissemination of superior varieties that are adaptive to various abiotic stresses requires continued support through plant breeding programs, the provision of quality seeds, and farmer mentoring. Integrating adaptive varieties with soil amelioration, site-specific fertilization, water management, and precision agriculture technologies will be key to sustainably increasing rice productivity on suboptimal land.

3.4 Water Management

Water management is a crucial factor in determining the success of rice cultivation on suboptimal land. In swampy areas, water management aims to control water levels to reduce Fe and Al toxicity, while in dryland areas, the focus is on increasing water use efficiency. One widely recommended technology is **Alternate Wetting and Drying (AWD)** , an irrigation system that alternates between flooded and unflooded conditions. According to Bouman et al. (2007), AWD technology can save up to 30% on water use without reducing crop yields and, in some conditions, can even increase rice productivity. Furthermore, this technology also contributes to reducing methane emissions, thus supporting low-carbon agriculture.

3.5 Utilization of Microorganisms and Biofertilizers

of biofertilizer technology offers significant opportunities to increase the productivity of suboptimal land. Microorganisms such as **Azospirillum** , **Azotobacter** , **Bacillus** , **Pseudomonas fluorescens** , and mycorrhizal fungi can increase nutrient availability, improve root growth, and enhance plant resistance to environmental stress. Biofertilizers can also increase the efficiency of chemical fertilizer use, thereby lowering production costs. According to Vessey (2003), the use of functional microorganisms not only increases crop productivity but also improves soil quality by increasing biological activity and maintaining soil ecosystem balance. In suboptimal soils, combining biofertilizers with organic matter has been shown to provide a better response than single applications.

3.6 Application of Precision Agricultural Technology

Advances in digital technology have led to the emergence of the concept of **Precision Agriculture** , which enables more efficient, data-driven land management. This technology utilizes soil sensors, moisture sensors, satellite imagery, drones, geographic information systems (GIS), *the Internet of Things* (IoT), and artificial intelligence *to* monitor land conditions in real time. Soil sensors can be used to measure humidity, pH, temperature, and nutrient content, allowing for more accurate fertilizer and irrigation decisions. Drones and satellite imagery are used to monitor plant health, detecting early signs of nutrient deficiencies and pest infestations. Meanwhile, artificial intelligence algorithms can process climate, soil, and crop data into more precise management recommendations. According to Zhang et al. (2021), the application of precision agriculture can improve the efficiency of fertilizer and water use while increasing crop productivity in modern cultivation systems.

3.7 Integration of Suboptimal Land Management Strategies

Various studies have shown that no single technology can effectively address all the challenges associated with suboptimal land. Therefore, an **integrated management approach** combining soil amelioration, site-specific fertilization, the use of tolerant varieties, water management, biofertilizers, and precision agriculture is the most effective strategy. This technological integration can increase rice productivity, improve soil health, enhance input efficiency, and strengthen the resilience of production systems to climate change. This approach aligns with the concept of **Climate-Smart Agriculture** , which emphasizes increasing productivity, adapting to climate change, and simultaneously reducing greenhouse gas emissions (FAO, 2023; Lal, 2020).

3.8 The Effect of Integrated Technology Implementation on Rice Productivity

Various studies have shown that the application of integrated suboptimal land management technology can significantly increase rice productivity compared to conventional cultivation systems. This yield increase is achieved through a combination of various technologies, such as soil amelioration using dolomite, biochar, compost, and gypsum, site-specific fertilization, the use of adaptive superior varieties, water management, the use of biofertilizers , and the application of precision agriculture technology. The synergy between these technologies can improve the physical, chemical, and biological properties of the soil, thereby increasing the efficiency of water and nutrient use, optimizing plant growth, and increasing grain productivity. Based on various studies, the application of integrated technology can increase grain yields by around **15–40%** compared to conventional management, although the magnitude of the increase is influenced by agroecosystem conditions, soil fertility levels , the type of technology used, and the farmer's ability to implement the innovation (Mulyani et al., 2021; Agegnehu et al., 2017).

This increase in productivity is primarily due to improved environmental conditions for plant growth. The application of dolomite to acidic soils can increase soil pH, thereby reducing aluminum (Al) toxicity and increasing the availability of phosphorus (P), calcium (Ca), and magnesium (Mg). The addition of biochar and compost increases soil organic carbon content, cation exchange capacity (CEC), water retention capacity, and the activity of soil microorganisms that play a role in the nutrient mineralization process. Furthermore, the use of adaptive rice varieties combined with site-specific fertilization allows plants to utilize nutrients more efficiently, resulting in better vegetative and generative growth. In swampy and saline areas, water management and the use of tolerant varieties have also been shown to reduce the impact of environmental stress, thus maintaining plant productivity under unfavorable conditions (Lal, 2020; Fageria & Baligar, 2008).

The development of digital technology is further enhancing the effectiveness of suboptimal land management. The use of soil sensors, *the Internet of Things* (IoT), drones, satellite imagery, and artificial intelligence (*AI*) enables real-time monitoring of land conditions, enabling more precise decisions regarding irrigation, fertilization, and pest control. Precision agriculture technology not only increases productivity but also reduces production costs through more efficient input use and reduces negative environmental impacts. Therefore, the integration of conventional and digital technologies is a key direction for the development of suboptimal land management in the future to support a productive, climate-adaptive, and sustainable rice production system (Zhang et al., 2021; FAO, 2023).

The combination of various technologies can increase grain yields by around 15–40% compared to conventional management, depending on land conditions and the technology applied.

4. Challenges in Suboptimal Land Management

Although various technological innovations have been proven to increase rice productivity on suboptimal land, their implementation at the farmer level still faces numerous obstacles. These challenges relate not only to technical aspects of cultivation but also to economic, social, and institutional factors, as well as the increasingly complex impacts of climate change. Successful management of suboptimal land depends heavily on the ability to integrate technology with the biophysical conditions of the land, farmer capacity, government policy support, and the availability of adequate production facilities. Therefore, developing suboptimal land requires a multidisciplinary approach involving various stakeholders, from the government, researchers, extension workers, and farmers (Mulyani et al., 2021).

One of the main challenges is **the high cost of soil amelioration** . Most suboptimal land requires pretreatment in the form of dolomite, lime, biochar, compost, manure, or gypsum to improve the physical and chemical properties of the soil. The relatively high demand for ameliorants increases production costs, especially for small-scale farmers with limited capital. Furthermore, the distribution of ameliorant materials in some areas is still limited, resulting in higher prices. Fageria and Baligar (2008) explain that although amelioration can significantly increase productivity, the large initial investment is often a barrier to technology adoption by farmers.

The next challenge is **the low level of technology adoption** among farmers. Various studies show that many farmers still use conventional cultivation methods due to limited knowledge, limited access to technological information, and a lack of assistance from agricultural extension workers. Technologies such as site-specific fertilization, the use of biofertilizers, alternating *wetting and drying irrigation systems* , and precision agriculture have not been widely implemented because they are considered more complicated than traditional cultivation methods. Rogers (2003) explains that the successful adoption of innovation is greatly influenced by farmers' perceptions of the technology's benefits, ease of implementation, and available institutional support.

Furthermore, **limited access to quality agricultural inputs** is also a significant obstacle. In some areas where suboptimal land is being developed, farmers still experience difficulties obtaining superior seeds, quality fertilizers, biofertilizers, and ameliorant materials in sufficient quantities and at affordable prices. This situation prevents the technology recommended by research results from being optimally implemented in the field. Mulyani et al. (2021) emphasize that the success of suboptimal land optimization is determined not only by the availability of technology, but also by the distribution system of production inputs, financial support, and adequate market access.

Climate change is becoming a growing challenge in suboptimal land management. Rising temperatures, changing rainfall patterns, increased frequency of flooding, drought, and seawater intrusion are causing growing environmental conditions to become increasingly uncertain. In swamplands, changing hydrological patterns can increase the risk of iron toxicity and prolonged flooding, while in marginal drylands, longer dry seasons increase the risk of drought and reduce fertilizer use efficiency. The IPCC (2023) report indicates that the agricultural sector is one of the most vulnerable to the impacts of climate change, requiring a more comprehensive adaptation strategy through the implementation of *Climate-Smart Agriculture* .

On the other hand, developments in digital technologies such as **the Internet of Things (IoT), soil sensors, drones, satellite imagery, and artificial intelligence (AI)** offer new solutions for suboptimal land management. However, the implementation of these technologies still faces various obstacles, such as limited digital infrastructure in rural areas, high investment costs, low digital literacy among farmers, and limited availability of assistants with competency in precision agriculture. Therefore , the success of digital transformation in agriculture requires policy support, increased human resource capacity, and collaboration between the government, universities, research institutions, and the private sector.

Overall, the challenges of managing suboptimal land demonstrate that increasing rice productivity depends not only on technological innovation but also on the readiness of support systems, including financing, institutions, extension services, input distribution, and adaptation to climate change. With appropriate policy support, strengthening farmer capacity, and the application of technologies tailored to local conditions, suboptimal land has significant potential to become a primary source of increased rice production and support sustainable national food security.

5. Conclusion

Suboptimal land has enormous potential as a source for expanding rice cultivation areas to support national food security amid increasingly limited productive rice paddy fields due to land conversion, soil degradation, and climate change. Despite various limiting factors, such as soil acidity, aluminum (Al) and iron (Fe) toxicity, salinity, low organic matter content, nutrient deficiencies, and limited water management, various studies have shown that these constraints can be overcome through the application of appropriate, location-specific management technologies.

An integrated land management approach is the most effective strategy for increasing rice productivity on suboptimal land. Integration of soil amelioration using dolomite, biochar, compost, and gypsum, site-specific fertilization, the use of tolerant rice varieties, water management, biofertilizer utilization, and the application of sensor-based precision agriculture technology, the Internet of Things (IoT), remote sensing, and artificial intelligence (AI *)* has been proven to improve the physical, chemical, and biological properties of the soil, increase the efficiency of water and nutrient use, and increase grain productivity by around **15–40%** compared to conventional management.

However, successful management of suboptimal land still faces various challenges, including high amelioration costs, low levels of technology adoption by farmers, limited access to quality seeds and agricultural inputs, and the increasing impact of climate change. Therefore, successful development of suboptimal land requires synergy between technological innovation, institutional strengthening, government policy support, increased human resource capacity, and close collaboration between researchers, extension workers, the government, the private sector, and farmers. With this approach, suboptimal land has the potential to become a key pillar for increasing national rice production that is productive, adaptive to climate change, and sustainable.

6. Suggestions

The development of suboptimal land management in Indonesia needs to be directed toward the application of site-specific technologies tailored to the biophysical characteristics of each agroecosystem. The use of integrated technology packages that combine soil amelioration, site-specific fertilization, adaptive superior varieties, water management, biofertilizers, and precision agriculture technologies needs to be further expanded through dissemination and mentoring programs for farmers to increase innovation adoption. The government needs to strengthen policy support by providing superior seeds, ameliorant materials, biofertilizers, access to financing, and developing irrigation infrastructure and climate information systems. Furthermore, increasing the capacity of agricultural extension workers and strengthening farmer institutions are crucial factors in accelerating technology implementation at the field level. From a research perspective, further studies are needed on the long-term effectiveness of various combinations of suboptimal land management technologies on various soil types and agroecosystem conditions in Indonesia. Research also needs to be directed at developing climate-smart agriculture systems *that* integrate digital technology, artificial intelligence *,* remote sensing, field sensors, and big data analysis *to* support more accurate decision-making, improve resource efficiency, and strengthen the resilience of rice production systems to climate change. Thus, suboptimal land management can not only increase rice productivity but also support the achievement of a sustainable, resilient, and highly competitive national agricultural system.

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