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*Review*

# Agroecological Nutrient Management Strategy for Attaining Sustainable Rice Self-Sufficiency in Indonesia

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**Abstract:** Rice self-sufficiency is central to Indonesia's agricultural development, but the country is increasingly challenged by population growth, climate change, and arable land scarcity. Agroecological nutrient management offers solutions though optimized fertilization, enhanced organic matter and biofertilizer utilizations, and improved farming systems and water management. Besides providing enough nutrients for crops, the agroecological approach also enhances resilience to climate change, reduces the intensity of greenhouse gas emissions, and improves the biological functions of rice soil. Organic and bio fertilizers can reduce the need for chemical fertilizers. For example, blue-green algae may contribute 30–40 kg N ha$^{-1}$, while the application of phosphate solubilizing microbes can reduce the use of chemical phosphorous fertilizers by up to 50 percent. The country currently experiences substantial yield gaps of about 37 percent in irrigated and 48 percent in rain-fed rice. Achieving self-sufficiency requires that Indonesia accelerates annual yield growth through agroecological nutrient management from a historical 40 kg ha$^{-1}$ year$^{-1}$ to 74 kg ha$^{-1}$ year$^{-1}$. The aim is to raise the average yield from the current 5.2 t ha$^{-1}$ year$^{-1}$ to 7.3 t ha$^{-1}$ year$^{-1}$ by 2050. Simultaneously, controlling paddy field conversion to a maximum of 30,000 hectares per year is crucial. This strategic approach anticipates Indonesia's milled rice production to reach around 40 million metric tonnes (Mt) by 2050, with an expected surplus of about 4 Mt.

**Keywords:** agroecology; biochar; biofertilizers; climate change; greenhouse gases; inorganic fertilizers; nutrient management; organic matter; paddy field conversion; rice self-sufficiency; stonemeal

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## 1. Introduction

Indonesia heavily relies on rice as a staple food, serving as the main component of almost every meal and constituting a fundamental part of the daily diet. Rice cultivation plays a pivotal role in the country's economy, providing employment to millions in rural areas and supporting livelihoods and local economies. Food security, defined as equal access to sufficient, safe, and nutritious food necessary for all people [1], has been an economic, social, and research interest in the past few decades. However, rice self-sufficiency has remained the primary indicator of food security in Indonesia [2].

Rice production faces challenges due to the high and increasing population [3], land scarcity, and climate change. Its low management level results in a wide yield gap, representing the difference between the actual yield and the attainable yield in rice production [4]. We believe that agroecological nutrient management, combined with the control of paddy field conversion, will be the solution for attaining sustainable rice self-sufficiency in Indonesia.

Agroecological nutrient management refers to a sustainable and holistic approach to managing nutrients in agricultural systems. It involves the integration of ecological principles with agricultural practices to optimize nutrient use efficiency, minimize environmental impacts, and enhance long-term agricultural sustainability. It takes into account the complex interaction between crops, soil, microorganisms, and the environment to promote nutrient cycling, reduce nutrient losses, and improve soil fertility. It is a management approach based on agroecological principles that aim to increase farm productivity through the wise use of external inputs, sustaining ecosystem services, and valorizing ecological processes and ecosystem services [5,6]. This approach reduces reliance on chemical fertilizers and enhances the use of organic matter, biofertilizers, and the efficient use of water [7]. A recent study showed that agroecological nutrient management with a higher input of organic matter increased soil pH, the availability of potassium, calcium, and magnesium, potassium concentration in leaves, and mycorrhizal colonization [8]. Another study that increased reliance on legumes, integrated crop–livestock production, and use of soil amendments resulted in enhanced soil organic matter (and soil carbon) accrual. The effects in the long term were more consistent in terms of increase yields, yield stability, profitability and food security [9]. An agroecological approach is important for restoring degraded lands [5,10] and overcoming the yield gap [4]. Increasing concerns about the loss of natural habitats and biodiversity emphasize the importance of producing more rice on existing cropland by improving the efficiencies of nutrients, energy, water, and other inputs in an agroecological process [5,11,12].

The rice harvest area in Indonesia was about 10.6 million hectares (ha), and unhusked (paddy) rice (subsequently called "rice") production was about 54.5 million tonnes per year (Mt year$^{-1}$) (equivalent to 31.4 Mt milled rice—the average for 2020–2021). Rice yield was about 5.2 tonnes per hectare (t ha$^{-1}$). From 2000 to 2021, Indonesia imported a minimum of 0.25 Mt (in 2009) and a maximum of 2.75 Mt (in 2011) of milled rice. In 2021, the milled rice import was 407,741 tonnes, and the national production was 31.36 Mt (information about the milled rice import and national production is from Indonesia's Central Bureau of Statistics, www.bps.go.id, accessed on 11 November 2022). This means that Indonesia is barely reaching rice self-sufficiency.

As a populous country, dependence on rice import may make Indonesia vulnerable to international market price fluctuations. Although Dawe (2008) [13] doubted that price volatility and world market price distortion would be significant, the government policy is that national production must be increased to meet demand, and import must be eliminated or kept to a minimum.

Indonesia will likely become more dependent on rice import as its population increases [14] and the effects of climate change and uncontrolled paddy field conversion worsen [15]. The population growth rate in Indonesia may be decreasing with increased education level (population growth data are from World Bank Open Data, https://data.worldbank.org/indicator/SP.POP.GROW?locations=ID, accessed on 11 November 2022), but it will tend to stay positive until 2050.

The effects of climate change may be intensifying, and will depend on the ability of countries to adapt and comply with their pledges on climate change mitigation as stipulated in the 2021 Glasgow Climate Pact (to learn more about the 2021 Glasgow Climate Pact, see https://www.un.org/en/climatechange/cop26, accessed on 3 January 2023). Meanwhile, controlling paddy field conversion appears to be more and more challenging, not only in Indonesia [16] but also elsewhere in the world [17]. These three factors—population growth, climate change, and land conversion—are obstacles to attaining rice self-sufficiency. Adapting to and mitigating climate change is essential [18], and failing to control rice field conversion will hinder the rice self-sufficiency objective [19].

There are two approaches to increasing rice production: extensification and (sustainable) intensification. Extensification is becoming more and more difficult due to arable land scarcity [19]. Furthermore, the conversion of existing rice-producing areas is occurring at an alarming rate [20], resulting in shrinking paddy field areas. Hence, intensification has a greater opportunity to contribute to increased rice production. The actual average rice yield of about 5.2 t ha$^{-1}$ is far below the potential yield of irrigated rice, ranging from 8.3 t ha$^{-1}$ to 11.7 t ha$^{-1}$, or the rain-fed rice yield, ranging from 7.9 t ha$^{-1}$ to 12.1 t ha$^{-1}$ [21].

These data clearly show a great opportunity to close the yield gap to increase national rice production.

Yuan et al. (2022) [14] suggested that yield is attainable up to 80% of potential yield under irrigated or 70% of potential yield under rain-fed rice systems. Increasing yield to above 80% of the potential yield may not be feasible economically, and it may pose a threat to the environment due to the excessive input it requires [11,12].

Nutrient deficiencies and imbalances have been the main problem in Indonesian rice fields [22,23]. This aspect will be discussed as an avenue for narrowing the rice yield gap from a nutrient management perspective. The benefits and feasibility of using biochar are also discussed. The effects of climate change on food security require serious attention; hence, we discuss adaptation and mitigation strategies for managing paddy soils [18]. We also touch upon the problem of paddy field conversion, which may hinder achieving the rice self-sufficiency target. Finally, we provide recommendations to improve the current policy, including the challenges that must be overcome.

This paper presents a literature review of paddy field nutrient management systems, linking them with agroecological principles. It provides an overview of paddy field nutrient status and fertilization and discusses the enhancement of agroecological functions resulting from agroecological nutrient management practices.

We conducted a comprehensive literature review on agroecological nutrient management aimed at achieving rice self-sufficiency in Indonesia. This involved a systematic search and analysis of the available literature, including relevant journals, reports, and scholarly articles related to agroecological approaches to nutrient management for rice cultivation and self-sufficiency in rice production in Indonesia. While we prioritized publications from the last 20 years, older relevant literature was included when necessary.

Our literature search utilized databases such as Scopus, Web of Science, Google Scholar, and relevant institutional repositories. We used keywords related to agroecology, nutrient management, rice cultivation, rice self-sufficiency, water management, methane emissions, nitrous oxide emissions, biofertilizers, biochar, and Indonesia. The collected literature was screened based on the focus of our review. Key information was extracted from selected studies, and findings were synthesized to identify common trends, challenges, and successful approaches to agroecological nutrient management for achieving rice self-sufficiency. The summarized findings were interpreted in terms of their implications for rice production and self-sufficiency in Indonesia.

Limitations to this review process may arise due to publication bias, in which certain topics might be overrepresented while others are underrepresented, potentially skewing the overall findings. Despite evaluating the robustness of the reviewed studies, variations in the quality and reliability of studies may persist, possibly leaving out crucial developments unsupported by scientific publications or lacking published time series data, especially concerning nutrient status.

Additionally, we offer a brief scenario analysis regarding closing the yield gap, controlling paddy field conversion, and implications for rice self-sufficiency until 2050, including calculations for national rice consumption and land conversion rates.

To the best of our knowledge, no scientific papers have comprehensively discussed various aspects of paddy rice nutrient management systems linked with agroecological principles. Therefore, this paper is relevant not only for Indonesian conditions but also for other countries where lowland rice constitutes a significant agricultural system.

## 2. Paddy Rice Soils and Their Nutrient Status

### 2.1. Paddy Rice Soils

About 70% of Indonesian paddy soils belong to the Inceptisol, Entisol, and Vertisol soil orders. Vertisols comprise about 7% of Indonesian paddy soils [24]. About 22% are paddy soils of higher elevation in volcanic areas, and they belong to the Ultisol, Inceptisol, Andisol, and Alfisol orders.

Inceptisols generally have a low pH, low cation exchange capacity (CEC), and low soil organic C and N contents. However, the fertility of Inceptisols derived from alluvium varies depending on the nutrient status of the parent materials. Vertisols have a relatively high pH, high cation exchange capacity (CEC), and high macro- and micronutrient content [24,25]. For example, the percentage of soils with a high K status is high in Central and East Java (Figure 1), where Vertisols are the dominant paddy soils, although management factors could also lead to a high K status. Rice fields of the Vertisol order are high in clay content and hence very likely have a low saturated hydraulic conductivity, which makes the leaching of cations and anions, such as potassium ($K^+$) and nitrate ($NO_3^-$), typically minimal [25]. This indicates a better nutrient efficiency in Vertisols compared to that in Inceptisols and Ultisols [26]. Ultisols are mostly low in CEC and exchangeable cations [25]; hence, they require relatively high inputs of basic cations.

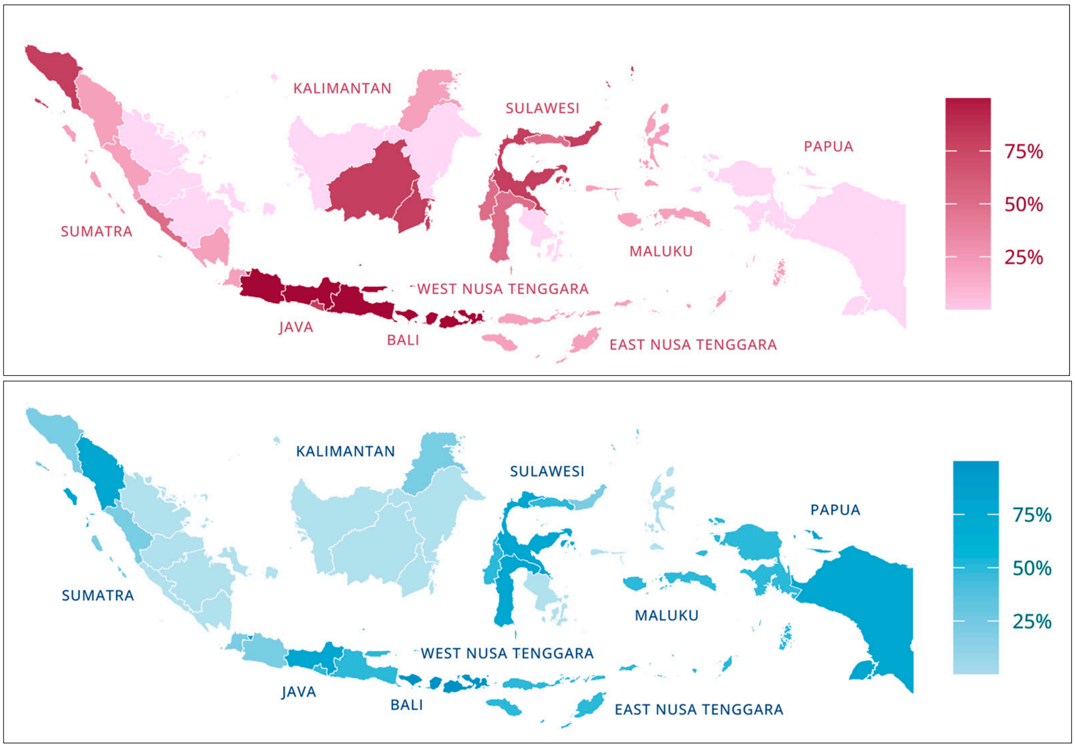


**Figure 1.** Maps showing the percentage of paddy field areas with high phosphorous (P) status (>174 mg $kg^{-1}$ P) (**upper**) and the percentage of paddy field areas with high potassium (K) status (>166 mg $kg^{-1}$ K) (**lower**) (adapted from Widowati et al., 2021) [26].

When the dry (unflooded) land systems are converted to paddy field systems, the soil undergoes physical and chemical transformations. Flooding leads to a decrease in soil redox potential and increases the availability of phosphorus (P) and calcium (Ca) for plant uptake. Further, plow pan forms in paddy fields when soil is compacted by heavy equipment, humans, or animals [27], reducing water loss through percolation and nutrient loss through leaching. C stock tends to increase [28] and soil pH tends to reach near neutrality in paddy soils [29].

### 2.2. Essential Nutrients

The nutrients N, P, K, Ca, sulfur (S), Mg, C, oxygen (O), and hydrogen (H) are grouped into macronutrients, i.e., nutrients essential to plants, and are needed in relatively large amounts. Of these, Ca, Mg, and S are also called secondary macronutrients because they are needed by plants in relatively smaller amounts than N, P, and K, and are usually applied to the soil from organic matter, lime, and other sources. The macronutrients C, H, and O are abundant in nature and are taken up by plants in the forms of carbon dioxide ($CO_2$), water ($H_2O$), or oxygen ($O_2$) through roots and leaves [30].

Micronutrients such as Zn, Cu, boron (B), manganese (Mn), molybdenum (Mo), Fe, silicon (Si), and chlorine (Cl) are important in metabolic activities and enzymatic processes and help in plant growth and production [31]. Micronutrient availability to plants is regulated by various soil factors, including soil texture, soil pH, organic matter content, clay content, soil moisture, nutrient interactions, microbial activity, redox potential, and aeration [32].

Micronutrient cations, such as Fe, Zn, Cu, and Mn, are either in the soil solution or are adsorbed at soil mineral exchange sites [33,34]. Organic matter is an important secondary source of micronutrients in soil. Soils that receive regular additions of organic residues or manure rarely show micronutrient deficiencies. Incorporating soil amendments and fertilizers into the soil can also contribute to micronutrient availability [32] and micronutrient efficiency [35,36]. Balanced P and K fertilization also improves the micronutrient balance, especially of Zn and Cu [26].

There are two types of lowland rice fields in Indonesia: irrigated and rain-fed rice fields. Irrigated fields are normally flooded during the crop season, with the waterhead two to five centimeters above the soil's surface. Of the total paddy field area of about 7.4 million ha across Indonesia, about 4 million ha are irrigated [37]. Irrigated paddy fields benefit from a secure water supply and the transport of nutrients from irrigation water, but that is not the case for rain-fed paddy rice areas [38].

### *2.3. Nutrient Status of Indonesian Paddy Fields*

The macronutrients N, P, and K are important for rice production. Among the three, K is the most abundant on the Earth's surface. However, about 90–98% of this K is in the form of primary minerals that are not available for plant uptake, and only 1–2% of the nutrient is in the form available to plants [39]. In low-activity clay soils, such as most Ultisols and Inceptisols, K can move through the mass flow process and leach from the surface to the lower layers during and after heavy rains. However, in permanent rice systems, K leaching can be minimized by the presence of a plow layer [22].

In soil, N is very mobile and can be easily lost due to evaporation or leaching; it also changes from one form to another, such as ammonium ($NH_4^+$) to $NO_3^-$, nitrous oxide ($N_2O$), or ammonia ($NH_3$). Rice plants are very responsive to the application of N fertilizer, but the fertilizer's efficiency is very low (i.e., <30%) [40]. Split application of N is a common practice to reduce N loss [26].

In soil, P exists as an inorganic form originating from P-containing minerals (such as apatite) and an organic form originating from organic matter. The availability of P in soil is low because it is bound to clay or organic matter. In soils with a low pH (4–5.5), P is fixed by iron (Fe) and aluminum (Al) oxides, whereas in soils with a high pH (7–8), it is fixed by Ca and Mg. Continuously applying large quantities of P fertilizer may cause P to accumulate in soil. Accumulated P can be taken up by plants if the soil reaction reaches optimal conditions for its release [22].

In the 1990s, rice fields in Java were considered to be saturated with P and K because of the continuous application of triple superphosphate and potassium chloride (KCl). However, a survey in Sumatra, Java, Sulawesi, and Nusa Tenggara indicated a reverse trend, where K application tended to be lower than the crop needed [41].

Nutrient status maps for P and K with scales of 1:50,000 have been compiled for 7259 subdistricts in the 34 provinces of Indonesia [26]. In Figure 1, we present only the high P and high K status maps of Indonesia. This nutrient map was developed based on potential soil P and K extracted with 25% hydrochloric acid (HCl). The P and K statuses were categorized as low (mg $kg^{-1}$) (<87 P; <83 K), medium (87–174 P; 83–166 K), and high (>174 P; >166 K).

The P status map shows that most paddy fields in Java, Bali and West Nusa Tenggara exhibit high percentages of areas with high P nutrient status, attributed to intensive management in these areas. However, in Sumatra and the western and eastern parts of Kalimantan, most paddy field areas show a low P status, due to high soil acidity and minimal influence of volcanic ash, especially in Kalimantan.

The K status map shows high percentages of paddy fields with high K status in West Java (may be due to management factors). Central Java and East Java also have more areas with a high K nutrient status, whereas NTT, Riau, and South Sulawesi were dominated by low K nutrient content (Figure 1).

Besides nutrient status maps, Indonesia also utilizes a paddy soil test kit (PUTS). PUTSs can be used by extension workers, or even by farmers, to assess soil P and K statuses, and a leaf color chart can be used to determine N status in plant tissue [42–44]. Based on PUTSs, NPK fertilizer application is 16–48% more efficient in areas where its application is excessive compared to common farmer fertilizer rates, and the yield increase is 6–13%. As of 2019, around 18,325 PUTSs had been distributed in Indonesia, mainly through government projects and programs as well as a small portion through individual sales [43]. However, efforts are needed to introduce this device to farmer groups in central rice production areas of Indonesia for more efficient and more balanced fertilizer application, i.e., ensuring that plants have access to an adequate supply of each nutrient at every growth stage.

Nutrient status maps are necessary to guide extension services on recommended domains and policymakers on fertilizer distribution. Previously available nutrient status maps for Indonesia were at a scale of 1:250,000, which could be used as a basis for fertilizer distribution at the provincial level. More detailed soil nutrient status maps with a scale of 1:50,000 can now be used as a basis for fertilizer recommendations at subdistrict and village levels [45,46].

Manure and inorganic fertilizers significantly augment soil-available Fe, Mn, Cu, and Zn content. Long-term inputs of organic amendments alter the properties of soil and increase its plant-available micronutrient content [36].

## 3. Agroecological Nutrient Management

In this section, we discuss several aspects of nutrient management, including soil nutrient status, fertilization using chemical, organic and biofertilizers, as well as other potential nutrients that can be exploited from local sources such as biochar.

### *3.1. Nitrogen, Phosphorous and Potassium Fertilization*

N, P, and K fertilizers are essential for increasing paddy rice yield and national rice production. However, fertilizer applications that are unbalanced and insufficient have contributed to low fertilizer efficiency and are ineffective for increasing crop yield.

Until at least early 2010, the uniform recommendation of 600 kg urea ha$^{-1}$ (276, N), 300 kg SP-36 ha$^{-1}$ (47, P), and 150 kg KCl ha$^{-1}$ (78, K) was still common [47], and this may have led to the excessive or deficient status of some or all nutrients. In early 2020, Indonesia developed a soil nutrient status map at a scale of 1:50,000. In Figure 1, we demonstrate only the map of high-status phosphorous (P) and potassium (K) for Indonesia.

The national level soil test approach in Indonesia classified the soil nutrient status into soils with low soil test P (<87 mg P kg$^{-1}$), for which the recommended P fertilizer is 17 kg P ha$^{-1}$. Soils with medium (87–174 mg P kg$^{-1}$) and high (>174 mg P kg$^{-1}$) P status are recommended to have 13 and 11 kg ha$^{-1}$ P fertilizer, respectively. Likewise, soils with low (<83 g kg$^{-1}$ K), medium (83–166 g kg$^{-1}$ K) and high (>166 g kg$^{-1}$ K) soil test K are recommended to have K fertilizer in amounts of 38, 30, and 25 kg ha$^{-1}$, respectively (Table 1).

Rice straw serves as an important source of K, allowing for a reduction in K application to half the recommended dose (only 30 kg K ha$^{-1}$) in cases of low soil K status, or a complete waiver in cases of medium and high K status soil [26].

**Table 1.** Recommended phosphorous (P) and potassium (K) for different paddy soil (P and K soil) test status (modified from Widowati et al., 2021) [26].

| Soil Nutrient Status | Fertilizer Recommendation |
|---|---|
| P status (mg P kg$^{-1}$) | Fertilizer rate (kg P ha$^{-1}$) |
| Low (<87) | 17 |
| Medium (87–174) | 13 |
| High (>174) | 11 |
| K status (mg K kg$^{-1}$) | Fertilizer rate (kg K ha$^{-1}$) |
| Low (<83) | 38 |
| Medium (83–166) | 30 |
| High (>166) | 25 |

Nitrogen (N) fertilization is based on yield target, whereby N rates are 112.5, 135, and 157.5 kg ha$^{-1}$ to attain yield targets of <6, 6–8, and >8 t ha$^{-1}$, respectively (Table 2) [26].

**Table 2.** Nitrogen (N) fertilizer rates based on yield targets (modified from Widowati et al., 2021) [26].

| Yield Targets (t ha$^{-1}$) | N Rates (kg ha$^{-1}$) |
|---|---|
| <6 | 112.5 |
| 6–8 | 135.0 |
| >8 | 157.5 |

Plant tissue analysis, also known as plant tissue testing, is recommended to complement soil tests or soil nutrient status maps. By measuring the nutrient level in the plant tissue, one can evaluate nutrient deficiency or nutrient surplus and address these imbalance problems accordingly. When farmers encounter unexplained issues with a plant, such as stunted growth or discolorization, tissue analysis can provide valuable information to diagnose these problems [48].

Plant tissue tests can complement soil tests. Plant tissue test results are compared against specific nutrient critical levels to guide fertilization practices aimed at adjusting plant tissue nutrient concentrations to meet these critical levels. For instance, Dobermann and Fairhurst (2000) [49] proposed critical levels of N, P and K for rice at 2.2%, 0.20%, and 1.4%, respectively.

In a study on nutrient sufficiency, P. Grassini [50] analyzed the concentrations of N, P, and K in rice plant tissues from samples collected in major paddy field production areas. The findings showed higher concentrations of N and P, but lower concentrations of K than the critical levels. This discovery emphasizes the necessity of regularly conducting soil tests in conjunction with plant tissue tests.

### *3.2. Micronutrient Fertilization*

One of the most limiting factors in rice tillering and spikelet sterility is Zn deficiency. The critical level of Zn in soil is 0.8 milligrams (mg) kg$^{-1}$ using diethylenetriaminepentaacetic acid (DTPA) extraction [49]. In soil, Zn deficiency causes stunted plant growth and reduces crop yield [51,52]. The recommended dose for Zn fertilization is 5–10 kg Zn ha$^{-1}$ and can be applied in the form of zinc oxide (ZnO), zinc chloride (ZnCl), or zinc sulfate ($ZnSO_4$) [53], or by dipping rice roots into a solution of 0.05% $ZnSO_4$ for five minutes [52]. Zn deficiency can also be alleviated by recycling rice straw because 60% of Zn in plant tissues is stored in straw [49].

Copper plays an important role in N, protein, and hormone metabolisms; photosynthesis and respiration; pollen formation; and activating the ligninolitic enzymes [49]. Cu deficiency affects grain formation, causes chlorosis and a loss of turgor in young leaves, and may favor the incidence of disease outbreak [51,52]. As much as 5–10 kg Cu ha$^{-1}$ can be applied for a five-year period, or rice seedling roots or rice seeds can be soaked in 1% copper sulfate ($CuSO_4$) solution for one hour [49].

Plants require B for carbohydrate metabolism, sugar transport, lignification, nucleotide synthesis, respiration, germination, and seed production extraction [44]. It is essential for the germination of pollen grains, the growth of pollen tubes, and seed and cell wall formation, and it promotes plant maturity [33]. Boron deficiency reduces plant height and may lead to the failure of panicle formation [52] and light chlorosis, the death of growing points, and deformed leaves with areas of discoloration [51].

In plants, Fe promotes the formation of chlorophyll. The reactions associated with Fe include the redox reactions of chloroplasts, mitochondria, and peroxisome [54]. The critical limit of Fe is less than 5 mg $kg^{-1}$ soil (using DTPA + calcium chloride [$CaCl_2$], pH 7.3 extraction). This condition is generally found in alkaline soils or in soils with a very high Fe-to-P ratio [49]. A deficiency of Fe can be seen as chlorosis or yellowing between the veins of young leaves [51].

Manganese functions as a part of certain enzyme systems. It helps in chlorophyll synthesis and also increases the availability of P and Ca. It has similar properties to Mg and can substitute for Mg in some enzyme systems [54]. The optimum Mn concentration in plants also decreases the incidence of diseases. A deficiency of Mn is characterized by chlorosis or yellowing between the veins of new leaves [51].

Molybdenum is required in the smallest amount of all the essential micronutrients. It is required to form the "nitrate reductase" enzyme, which reduces $NO_3^-$ to $NH_4^+$ in plants and is the first step of incorporating inorganic NO into organic N compounds. Other functions of Mo are present in nitrogenase (N fixation) and nitrate reductase enzymes; it plays an important role in plant nodulation and is needed to convert inorganic phosphates to organic forms in plants [33]. A deficiency of Mo results in a disrupted N metabolism [54].

Chlorine is required for turgor regulation, electrical charge balance, resisting diseases, and photosynthesis reactions [33]. A deficiency of Cl may cause chlorosis and wilting in young leaves [51].

Silicon is beneficial to the mechanical and physiological properties of plants and helps them overcome biotic and abiotic stresses. It enhances root water uptake, which helps regulate aquaporin activity and gene expression [55,56]. In addition, Si provides resistance against pathogens and pests as well as tolerance of droughts and heavy metals, and enhances quality and yield [51].

Most micronutrients can be supplied by organic matter [57]; hence, it is good practice to utilize organic matter where available. Although irrigation water can also contain micronutrients, care must be taken with water quality, especially for nonconventional irrigation water sources, because the water may contain heavy metals and other harmful elements [58].

### *3.3. Enhanced Use of Organic Fertilizers*

Organic fertilizers can be used in the form of organic matter, biofertilizers, or bioorganic fertilizers.

#### 3.3.1. Organic Matter

Organic matter plays an important role in enhancing soil properties and crop yield. The level of organic matter in soil can be increased by adding high-quality organic matter, such as composted plant residues or barnyard manure, into rice soils. Organic matter has many beneficial functions for soil, such as increasing soil water-holding capacity, improving soil structure, releasing macro- and micronutrients, improving soil biological activities, and increasing soil carbon stock [26,59,60]. For example, the application of 2 t $ha^{-1}$ dry weight of manure would provide about 16 kg N, 14 kg P, 31 kg K, and 16 kg Ca [61], in addition to other macro- and micronutrients. Organic matter application can increase organic C content from 0.78% to 0.83%, as well as increase soil CEC. Meanwhile, the application of 5 t $ha^{-1}$ rice straw containing 9 kg N and 26 kg K increased the rice grain yield from 2.39 t $ha^{-1}$ to 4.14 t $ha^{-1}$ compared to plots without rice straw recycling [62].

Rice straw typically contains 0.5% to 0.8% N, 0.07% to 0.12% P, and 1.16% to 1.65% K [63]. If all the rice straw yield (at a national average of 5 t $ha^{-1}$) is recycled, this equates to recycling 25 kg $ha^{-1}$ to 40 kg $ha^{-1}$ of N, 3.5 kg $ha^{-1}$ to 5.9 kg $ha^{-1}$ of P, and 58 kg $ha^{-1}$ to 83 kg $ha^{-1}$ of K per crop season. Almost 80% of K absorbed by rice plants is stored in rice straw. Therefore, it is highly recommended to return straw to the paddy field to prevent potassium depletion and provide a substantial amount of N, as well as a decent amount of P [26].

However, under saturated conditions, the addition of fresh organic matter may induce methane ($CH_4$) emissions. Furthermore, the application of easily decomposable organic matter, such as that containing high carbohydrates, can enhance N microbial immobilization. Conversely, the addition of organic matter containing high cellobiose and cellulose (intermediately decomposable compounds) will lead to a lower rate of N immobilization. On the contrary, when the added organic matter is dominated by recalcitrant compounds, such as lignins and tannins, it does not affect N immobilization. Notably, the C-to-N ratio per se is not a determinant of N immobilization [64].

Before applying organic fertilizers to soil, partially decomposed straw (compost) is recommended. Straw composting can be accelerated by adding N to reduce the C-to-N ratio. The decomposition process can also be accelerated by adding molasses to the windrows of straw [65]. This allows decomposition to take place in situ, hence reducing the labor needed for processing. By doing so, transportation costs and associated greenhouse gas (GHG) emissions can be reduced. Combining the use of organic fertilizers and inorganic fertilizers can increase rice yield significantly compared to only organic manure application [31,66].

Ando et al. (2022) [66] reported that applying inorganic fertilizer (NPK) with a proper amount of slaked lime ($Ca(OH)_2$) and rice straw compost is the most efficient fertilizer management system in paddy soils. Further, the application of lime and the recycling of straw increased rice yield, likely due to their effect on soil fertility and plant N uptake [67]. Another study also reported that incorporating rice straw or crop residues enhances both soil organic carbon (SOC) content and soil health, ameliorates climate change, and also increases beneficial soil microbe activities [68,69]. Rice straw application increased soil microbial respiration in the rhizosphere because it functions as a substrate and energy source for microbes [69]. Applying rice straw in combination with inorganic N fertilizer (80% N through rice straw and 20% through mineral fertilizer) resulted in maximum enzymatic activity compared to only crop residue or only mineral fertilizer application [68].

#### 3.3.2. Biofertilizers

Biofertilizers are microorganisms capable of increasing nutrient availability and improving soil health. The use of biofertilizers can increase soil nutrient availability and can also reduce soil pathogens [69]. The following sections discuss several types of biofertilizers that have been developed in Indonesia.

#### 3.3.3. N-Fixing Biofertilizer

N-fixing biofertilizer comprises the beneficial miroorganisms that convert $N_2$ into $NH_3$ [70]. The process of converting $N_2$ into $NH_3$ via diazotrophic microbes allows the total N content to be replenished and the fixed N regulates crop growth and yield [71]. N-fixing biofertilizer has been demonstrated in free-living microorganisms with anaerobic fixation (e.g., *Clostridium pasteurianum*) and aerobic fixation (e.g., *Azotobacter chroococcum*). Other prokaryotic organisms include cyanobacteria and archaebacteria. Symbiosis in the root systems of nonleguminous plants (e.g., *Frankia* spp.) and leguminous plants (e.g., *Rhizobium* and *Bradyrhizobium*) and an associative fixation between nonsymbiotic microorganisms (e.g., *Azospirillum* spp.) growing on the root systems of nonleguminous plants, but without forming nodules, also increases N availability to plants [70]. N-fixing groups also include green S bacteria, firmibacteria, actinomycetes, and proteobacteria. Nitrogenase is the key enzyme that carries out the conversion of dinitrogen into $NH_3$ during the process of N fixation [70,71].

Biological nitrogen fixation plays an important role in restoring soil fertility and ecosystem sustainability. N-fixing bacteria can provide 50–70 kg N-urea ha$^{-1}$ to crops [72] and is important for restoring agroecological functions and reducing the yield gap in staple food production by increasing soil fertility and generating income for farmers [73].

A study by Razie and Anas (2008) [74] showed that *Azotobacter* and *Azospirillum* inoculation increased rice growth with their ability to fix $N_2$ from the atmosphere. The increase in the total N content of soil was followed by an increase in the total N content of the plant tissue. *Azotobacter* spp. and *Azospirillum* spp. also increase root and shoot growth in rice plants. When *Azotobacter* is used as a biofertilizer and is combined with 50% NPK fertilization, it significantly increases the growth and production of grain and matches the growth and production of grain with 100% NPK fertilization [75].

N-fixing blue-green algae (BGA), such as *Nostoc* sp., *Anabaena* sp., *Tolypothrix* sp., and *Aulosira* sp., have the potential to fix $N_2$ and are used in paddy fields [76]. BGA are photosynthetic prokaryotic microorganisms which are capable of N fixation because they contain nitrogenase. They also benefit rice plants by producing growth-promoting substances [77]. BGA may contribute 30–40 kg N ha$^{-1}$ to the ecosystem. Grain yield increased from 2000 kg ha$^{-1}$ to 2300 kg ha$^{-1}$ with algalization, and from 3000 kg ha$^{-1}$ to 3200 kg ha$^{-1}$ under the treatment of 50 kg Urea-N ha$^{-1}$ with algalization. In general, algal inoculation (where effective) increases yield by about 14% [78]. In the plants treated with BGA, N uptake was higher than those of the untreated control [77]. A study by Setiawati et al., 2020 [79], demonstrated that the application of green manure increased soil N content from 0.10% to 0.20% and organic C content from 0.8% to 2.0%.

The application of a 50% dose of NPK fertilizer, along with 7 t ha$^{-1}$ of Azolla and 25 t ha$^{-1}$ of a compound biofertilizer containing Azotobacter, Azospirillum, N-fixing bacteria, and P-solubilizing bacteria, matched the yield of full-dose NPK fertilizers. This implies that Azolla and the compound biofertilizers compensated for about 50% of N, P and K needs, relative to a full NPK dose (138 kg ha$^{-1}$ of N, 7.8 kg ha$^{-1}$ of P, and 41 kg ha$^{-1}$ of K) [80].

Study by Setiawati et al., 2020 [79] reported that using 10 t ha$^{-1}$ of goat manure and 10 t ha$^{-1}$ of goat manure in combination with either 10 t ha$^{-1}$ of Azolla or 2 t ha$^{-1}$ Sesbania green manure, or 5 t ha$^{-1}$ Azolla plus 1 t ha$^{-1}$ Sesbania green manure, did not show a significantly different response of rice grain yield, ranging from 4.4 to 5.8 t ha$^{-1}$. This implies that nutrients supplied by 10 t ha$^{-1}$ goat manure sufficed for the crop's needs, and that additional green manure was not necessary with such a high-level goat manure application.

Similarly, another study [81] using either 10 t ha$^{-1}$ or 20 t ha$^{-1}$ fresh *Azolla pinnata* or powdered compost of either 2.5 or 5 of *Azolla pinnata* did not affect rice grain yield relative to the control treatment without Azolla application. This pot study applied blanket fertilizers equivalent to 46 kg ha$^{-1}$ of N, 8 kg ha$^{-1}$ of P, and 41 kg ha$^{-1}$ of K.

In general, however, when paddy fields are inoculated with BGA, rice grain yield increases by 7% to 22% [82–85].

#### 3.3.4. Phosphate-Solubilizing Microbes

Phosphate-solubilizing microorganisms (PSMs) play a critical role in the soil's P cycle. They achieve this by mineralizing organic P, solubilizing inorganic P minerals, and storing a significant amount of P in biomass [86,87].

PSMs, whether phosphate-solubilizing bacteria (PSB) or phosphate-solubilizing fungi (PSF), produce organic acids such as citric acid, glutamate, succinate, lactate, oxalate, glyoxylate, malate, fumarate, tartrate, and $\alpha$-ketobutyrate. These acids can bind Ca, Al, and Fe, facilitating phosphate availability to plants in the form of dihydrogen phosphate ($H_2PO_4^-$) [88].

PSMs isolated from bulk soils and rhizospheres have been shown to hydrolyze P by releasing phosphatases, playing a major role in P mineralization in most soils [86]. Puspitawati and Anas (2013) [89] succeeded in isolating PSM capable of dissolving phosphate sources such as calcium phosphate [$Ca_3(PO_4)_2$], aluminum phosphate ($AlPO_4$), and ferric phosphate ($FePO_4$), increasing the solubility of P from 65% to 135%. The application of PSM to paddy soils significantly increased rice plant growth and P uptake, and reduced chemical P fertilizer usage by up to 50%.

#### 3.3.5. K-Solubilizing Microbes

One way to increase the solubility of K from K-containing minerals or rocks involves the use of K-solubilizing microbes (KSMs), including K-solubilizing bacteria or K-solubilizing fungi. Various groups of rhizobacteria and fungi are involved with the solubilization of K minerals in the soil system [90]. A consortium of rhizobacteria, including *Bacillus edaphicus*, *Bacillus mucilaginosus*, *Bacillus circulans*, *Acidothiobacillus ferrooxidans*, *Paenibacillus sp.*, *Pseudomonas*, and *Burkholderia* demonstrates effective K-solubilizing abilities [90]. *Aspergillus terreus* also exhibits a high capacity to dissolve minerals and rocks containing K. These microbes are ubiquitous, and their presence depends on structure, texture, organic matter, and related soil properties [90,91].

Overall, biofertilizers that have been well developed in paddy fields include free-living or symbiotic microbes which help N fixation and PSMs. Among the various biofertilizers, N-fixing microbes (i.e., BGA) are some of the most commonly used and can increase grain yield by 200–450 kg $ha^{-1}$ [78]. Scaling up their application is an important strategy for increasing rice yield.

#### 3.3.6. Bioorganic Fertilizers

Bioorganic fertilizers are organic fertilizers that are improved by adding beneficial microbes such as $N_2$ fixers, PSMs, KSMs, and antagonistic microbes. Bioorganic fertilizers are used to reduce chemical fertilizer use, improve soil properties, and reduce environmental pollution.

The application of rice straw enriched with *Azotobacter* was able to reduce the use of NPK fertilizers by 25%. The use of organic straw fertilizer enriched with *Azotobacter* without artificial fertilizers increased soil $NO_3^-$ and $NH_4^+$. The use of rice straw enriched with *Azotobacter* and a 100% dose of NPK fertilizers was able to increase the rice grain harvest compared to the application of N, P, and K without organic fertilizer [76]. Bioorganic fertilizers reduced inorganic fertilizer use by about 25–30% and increased rice yield by about 25% [92]. The application of 50% NPK and bioorganic fertilizer increased 2.35 t $ha^{-1}$ grain yield and 3.39 t $ha^{-1}$ straw yield compared to the application of 50% NPK without bioorganic fertilizer. This yield increase was attributed to the supply of P and K from organic fertilizers and the increased availability of these nutrients due to the solubilizing microbes.

### *3.4. Other Locally Exploitable Nutrient Sources*

Besides chemical and organic fertilizers, there are many other sources of nutrients, including soil ameliorants such as agricultural lime, biochar, and crushed natural minerals, also called stonemeal.

Lime, especially dolomitic lime, has been widely used in Indonesia. Dolomitic lime can improve the microbial activity of acidic soils and increase crop yields [93,94]. Besides providing Ca and Mg, dolomitic lime also increases soil nutrient availability, such as N, and P, in acid soils [94–96].

Liming and applying straw increased soil N availability and the activities of soil enzymes involved in both C and N cycling and, hence, rice yield [67]. The application of dolomitic limestone increased K, Ca, Mg, and Mn content in the leaves [97]. Additionally, calcite or dolomite lime can be used as a soil amendment on rain-fed paddy fields with a low pH or low Ca and Mg contents [40]. Lime application also can reduce cadmium (Cd) and lead (Pb) accumulation in rice [98–102].

Biochar is a char produced from organic matter via thermal processing under depleted $O_2$ concentrations (pyrolysis) [103,104]. Applying biochar in combination with cattle manure increased soil organic C; CEC; available P; exchangeable K, Ca, and Mg; and nutrient uptake by crops [105]. Biochar also can be used as a soil amendment in acidic soils to improve soil P and reduce exchangeable Al and soluble Fe, as well as to significantly increase rice biomass [106] and yield [107].

Biochar improves soil's physical, chemical, and biological properties. Biochar improves soil's chemical properties by increasing nutrient retention and availability. Biochar decreases soil bulk density and increases saturated hydraulic conductivity. Incorporating biochar into soil increases the microbial population in the microsphere because the biochar surface changes soil conditions and makes it favorable for microbial activity in the soil [108,109].

Rice husk biochar (RHB) contains 1.12 mg $kg^{-1}$ of N, 0.98 mg $kg^{-1}$ of P, 184 mg $kg^{-1}$ of Mg, 168 mg $kg^{-1}$ of Si, 225 mg $kg^{-1}$ of Ca, and 176 mg $kg^{-1}$ of K. Therefore, its application to the soil improves the soil's nutrient status. The application of 10 t $ha^{-1}$ RHB significantly increases rice grain yield to 4.6 t $ha^{-1}$ compared to 2.6 t $ha^{-1}$ under the control treatment without biochar. Both the RHB and control plots received 25 kg $ha^{-1}$ of K, 26 kg $ha^{-1}$ of P, and 150 kg $ha^{-1}$ of N [110]. Another study using rice straw biochar resulted in 20–22% higher rice grain yield [111].

Stonemeal (i.e., ground stone containing high amounts of K and other macro- and micronutrients) has not been widely exploited in Indonesia. Considering the high price of conventional K fertilizer (KCl), the use of stonemeal seems promising. Stonemeal can rejuvenate nutrient-poor soils because some types of stonemeal are rich in K, P, Ca, Mg, and various micronutrients [112,113].

Indonesia possesses K-bearing minerals, such as K-feldspar and leucite (an aluminosilicate mineral), that contain most essential nutrients, including 4–20% of K [96]. Various techniques such as mechanochemistry, leaching, alkali fusion, and bioleaching can process these minerals into K fertilizers [114]. In Pati Regency, Central Java, Indonesia, K-bearing rocks are prevalent in alkaline and subalkaline formations characterized by low silica content and high alkalinity. These formations, including leucite, plagioclase, pyroxene, and opaque minerals, exhibit a potassium oxide ($K_2O$) content between 1.94% and 8.61% [115]. This aligns with a prior study in Pati Regency noting $K_2O$ content between 1.92% and 8.79% in leucite, augite, pyroxene, quartz, and sanidine rocks [116].

It will be necessary to conduct a survey of basic cation-rich (especially K) minerals, followed by field testing and an economic feasibility assessment of stonemeal. If this study proves successful, its potential application extends not only to paddy rice but also to other agricultural sectors, such as oil palm and other intensively managed crops.

### *3.5. Improved Water Management Systems*

Sustainable intensification to increase food security will require proper water management in addition to the use of high-yielding varieties and agronomic practices [117,118]. To increase water availability and mitigate the effects of drought in agricultural areas, irrigation management will need to be improved, as will the management of proper planting time [119–122]. Water is responsible for increased agricultural production, so it is crucially important to improve irrigation and water use efficiency [123].

The System of Rice Intensification (SRI) is one water use efficiency strategy [124–126]. The SRI emerged from on-farm experimentation in Madagascar, where existing norms of paddy rice were radically amended by reducing planting density, improving soil with organic matter, reducing the application of water, and the early transplantation of rice seedlings. Organic fertilizers are used in addition to chemicals. The SRI can increase N and P availability and soil microbial C activity [127,128]. The SRI method has a positive influence on rice root development, optimizing nutrient absorption in the soil [129]. Rice growth and production is better under the SRI than conventional rice cultivation [130–132], as shown in Table 3.

**Table 3.** Comparison of rice yield in conventional cultivation and the System of Rice Intensification (SRI).

| Method | | Increase | Reference |
|---|---|---|---|
| Conventional | SRI | | |
| t ha$^{-1}$ | t ha$^{-1}$ | % | |
| 6.0 | 7.9 | 32 | Bakrie et al., 2010 [130] |
| 3.6 | 4.3 | 22 | Razie et al., 2013 [131] |
| 7.0 | 9.0 | 29 | Hidayati and Anas 2016 [132] |
| 5.4 | 7.2 | 33 | Subardja et al., 2016 [133] |
| 4.5 | 6.4 | 42 | Moser and Barrett 2003 [134] |
| 3.8 | 4.6 | 22 | Tsujimoto et al., 2009 [135] |
| 4.8 | 7.6 | 58 | Styger et al., 2011 [136] |

The SRI improves plant physiological processes and characteristics, including longer panicles, more grains per panicle, a higher proportion of grain filling, deeper and better distributed root systems, and a higher number and larger leaves [132,136], as well as improved water-use efficiency [136,137].

However, despite the voluminous research data showing the dramatic advantages of the SRI, its adoption at farmer level is sluggish because the method requires significant additional labor input and specific management techniques that are challenging for smallholders [134]. Some studies have also reported no significant increase in paddy yields under the SRI compared to conventional rice management systems [135]. Incentives for SRI implementation are lacking; SRI rice does not command a premium price and it requires greater water regulation efforts than conventional systems [120,138]. Controversies persist in the literature regarding the associated benefits of grain yield and the SRI's reduced water use [139–141].

From the above discussion, it is clear that the overall principle of improving agroecological function to increase crop yield can be reached by improving nutrient balance, optimizing soil biological activities, increasing soil organic matter content, and improving the efficiency of agricultural input and water management.

### 3.6. Farming Systems and Crop Rotation

In an agroecological nutrient management system for paddy rice, diverse crop rotations can benefit soil health, nutrient cycling, and overall sustainability. In irrigated paddy rice systems in Indonesia, there are typically two to three crops per year. The third crop usually consists of secondary crops such as maize, soybean, peanut, or various vegetable crops [16]. This third crop improves nutrient utilization, cuts off pest and disease pressure, and increases overall yield and diversity. For instance, rotating lowland (flooded) rice with upland (oxic) maize improves root colonization by Archaea and bacteria [142].

Azolla, a water fern, can be used as green manure in paddy fields. Its symbiotic association with the cyanobacterium Anabaena azollae enables it to fix nitrogen from the atmosphere. Azolla is either incorporated into the soil before rice transplantation or grown as a dual crop along with rice [143]. It contributes to nitrogen supply, as discussed in Section 3.3.

The 'Minapadi', or rice–fish farming system, can be an effective rice farming system for increasing profitability if up to 4 t ha$^{-1}$ of compost is added [144]. Rice–duck culture is another example of an integrated farming system in paddy rice [145]. Ducks feed on weeds, dead leaves and pests (such as plant hoppers and leafhoppers) in the field, during which process they stir up the water and soil and fertilize the field so that soil nutrients are increased and the need for the application of fertilizers and pesticides is lowered [146]. Furthermore, rice–fish–duck is a promising ingenious system worth testing [147].

The key to success in these farming systems is to tailor crop rotations based on local agroecological conditions, crop compatibility, and the specific needs of the rice paddy system. Diversified rotations help maintain soil fertility, reduce pest and disease pressure, and improve overall resilience in paddy rice agriculture.

Summarizing Section 3 on agroecological nutrient management, the use of chemical (synthetic) fertilizers remains vital for national level rice production to ensure nutrient sufficiency. Indonesia's recent soil nutrient status map [26] facilitated tailored recommendations, specifying fertilizer rates at subdistrict level based on soil test results for phosphorous (P) and potassium (K) statuses. Nitrogen (N) fertilization aligns with yield targets for optimal levels. For more detailed site-specific recommendations, the use of a soil test kit is recommended. Complementing soil tests, plant tissue analysis aids in diagnosing nutrient deficiencies or surpluses, and is crucial for addressing productivity issues.

However, apart from synthetic fertilizer application, there are other sources of macro- and micronutrients, as well as materials that can enhance nutrient recycling. These include organic matter, biofertilizers, and other local nutrient sources such as biochar, lime, and stonemeal. These supplementary nutrient sources can not only reduce dependence on synthetic fertilizers, but also improve soil health and provide various agroecological functions (see Section 4). The ability of these alternative nutrient sources to supply or recycle nutrients varies. Table 4 shows potential amounts of nutrient contributions from these alternative sources.

**Table 4.** Potential nutrient contributions from organic matter, biofertilizers, and other soil ameliorants.

| **Treatments** | **Potential Nutrient Contribution** | | | | **Yield Increase ($t\ ha^{-1}$)** | **References** |
|---|---|---|---|---|---|---|
| | **N** | **P** | **K** | **Micronutrients** | | |
| Manure, 2 $t\ ha^{-1}$ (dry weight) | 16 $kg\ ha^{-1}$ | 14 $kg\ ha^{-1}$ | 31 $kg\ ha^{-1}$ | NA | NA | [61] |
| Rice straw (5 $t\ ha^{-1}$) | 25–40 $kg\ ha^{-1}$ | 3.5–5.9 $kg\ ha^{-1}$ | 58–83 $kg\ ha^{-1}$ | NA | From 2.4 to 4.1 $t\ ha^{-1}$ | [62,63] |
| Azotobacter + 50% of NPK normal dose | 50% † | NA | NA | NA | No yield decline | [75] |
| 50% NPK (69 kg N, 4 kg P, 21 kg K $ha^{-1}$) + 7 $t\ ha^{-1}$ of Azolla + 25 $kg\ ha^{-1}$ powder of Azotobacter, Azospirillum, N2-fixing bacteria, and P-solubilizing bacteria) | 69 $kg\ ha^{-1}$ Ł | 4 $kg\ ha^{-1}$ Ł | 21 $kg\ ha^{-1}$ Ł | NA | No yield decline | [111] |
| Blue-green algae | 30 to 40 $kg\ ha^{-1}$ | NA | NA | NA | From 2.0 to 2.3 $t\ ha^{-1}$ | [78] |
| Blue-green algae + 50 kg N $ha^{-1}$ | 30 to 40 $kg\ ha^{-1}$ | NA | NA | NA | From 3.0 to 3.2 $t\ ha^{-1}$ | [78] |
| Blue-green algae | NA | NA | NA | NA | 7–22% | [78,82–85] |
| P-solubilizing microbes | NA | 50% † | NA | NA | NA | [89] |

**Table 4.** *Cont.*

| Treatments | Potential Nutrient Contribution | | | | Yield Increase (t ha$^{-1}$) | References |
|---|---|---|---|---|---|---|
| | N | P | K | Micronutrients | | |
| K-solubilizing microbes | | | NA | | NA | [90,91] |
| Biochar | | | | | | |
| Stonemeal of K-bearing rocks | NA | NA | 1.6 to 7.3% ‡ | NA | NA | [115,116] |

NA = Data not measured or not available. † Percent contribution relative to conventional chemical fertilizer application; ‡ Percent of total potassium of applied stonemeal; Ł The values were implied as 50% of applied N, P, and K.

## 4. Improvement in Agroecological Functions

The agroecological management of paddy rice fields not only benefits crop growth and production, but also contributes to climate change mitigation, improves paddy system adaptation to climate change, and facilitates nutrient recycling [18,148].

### *4.1. Mitigation and Adaptation to Climate Change*

#### 4.1.1. Mitigation

Several management systems contribute to reducing GHG emissions, including the System of Rice Intensification (SRI), biochar application, organic matter application, and the planting of low-methane-emission varieties. The planting of low-methane-emission varieties is not discussed here as it is beyond the scope of this article, but readers can find a list of such varieties in Agus et al. 2022 [18].

GHG emissions (especially $CH_4$) of nearly 50 Mt carbon dioxide equivalent per year from paddy rice cultivation is the highest among emissions from the agricultural sector in Indonesia. Emissions of $N_2O$ are also suspected to be high from paddy rice systems because of the high rate of N application in intensive rice areas [18,28]. These $N_2O$ emissions fluctuate because of wetting and drying [149,150] resulting from alternate anaerobic and aerobic conditions, the condition favorable for $N_2O$ gas formation [18]. However, the increased $N_2O$ released during drying is compensated by decreased $CH_4$ emissions. Hence, it is the length of the submergence period of a paddy rice field that really determines $CH_4$ emissions, while the rate of N application is most important for $N_2O$ emissions [151]. When the paddy field is drained, $CH_4$ emissions decrease by about 1.22 kg ha$^{-1}$ day$^{-1}$ in the drained condition.

The SRI, with a higher number of unflooded days, offers significant $CH_4$ emission reductions. The longer flooded soil conditions of the conventional rice system lead to the higher activity of methanogen ($CH_4$-producing bacteria) compared to the prolonged aerobic conditions in the SRI [152]. Research demonstrates substantially lower seasonal $CH_4$ emissions in the SRI (20 kg ha$^{-1}$) in contrast to conventional systems (32 kg ha$^{-1}$) [153]. However, the frequent draining of SRI plots leads to intermittent aerobic soil conditions, potentially increasing $N_2O$ emissions compared to flooded fields [149,150]. Yet, other studies have reported reduced $N_2O$ emissions in the SRI [154–156].

Biochar has become increasingly popular because of its long residence time and, hence, conservation of C in soils [157–160]. For example, the application of 25 t ha$^{-1}$ of biochar increased soil C stock from about 35 t ha$^{-1}$ to about 57 t ha$^{-1}$ [161]. Similar results were found in the study of Sui et al. (2016) [162].

A study by Shen et al. (2014) [159] reported that the application of straw-derived biochar (22.5–48 t ha$^{-1}$) decreased $CH_4$ emissions. Another study also reported that the application of biochar amendment with N fertilizer may be a beneficial strategy to reduce net $N_2O$ and $CH_4$ emissions from paddy rice [160].

The application of organic fertilizer can significantly reduce GHG emissions. Specifically, the use of manure decreases $N_2O$ emissions by about 4.98 kg ha$^{-1}$ [163]. This aligns with other research where plots treated with rice straw and manure exhibited reductions in $N_2O$ emissions by 43% and 28%, respectively [164]. Win et al., 2021 [165], reported that cow dung manure reduced $CH_4$ emissions by 9.5% and $N_2O$ emissions by 33.7% compared to the control. Additionally, the application of rice straw, poultry manure and sugarcane bagasse resulted in decreased $N_2O$ emissions, offering mitigation in rice paddies [166]. The average annual $N_2O$ emissions from plots receiving 50% inorganic N fertilizer and pig manure were 51% lower than those from the 100% N treatment [167]. Furthermore, compared with the NPK treatment, the application of organic fertilizer alone led to a significant 32% reduction in $N_2O$ emissions [168].

Another study revealed that applying fresh and composted rice straw can reduce $N_2O$ emissions by 49% and 60%, respectively [169]. In areas where N application is traditionally excessive (e.g., due to the high subsidy of N fertilizers), improving the efficiency of N use can reduce $N_2O$ emissions [170].

Furthermore, paddy rice cultivation also mitigates climate change by increasing soil C stock by about 35% of its initial level over 20 years [28].

#### 4.1.2. Adaptation

Climate change is characterized by (i) erratic weather patterns, including changes in rainfall, increased frequency of extreme events like floods or droughts, and rising temperatures; (ii) rising sea levels, posing a risk of salinization in low-lying paddy fields, impacting soil fertility and crop growth; and (iii) outbreaks of pests and diseases, which threaten rice yields. These three factors heighten vulnerability in paddy fields and hinder the potential for increasing rice yield. Therefore, adapting to climate change is crucial in Indonesia to effectively manage these climate-related risks [171].

Agroecological nutrient management plays a pivotal role in enhancing resilience in paddy farming against climate change because balanced fertilization improves crop vigor, and in turns contributes significantly to a plant's resilience against the impacts of climate change. Vigorous crops exhibit better tolerance to drought, extreme temperatures, and changes in precipitation patterns. They can better withstand periods of water scarcity or excess, temperature fluctuations, and other environmental stresses. Vigorous plants tend to also have stronger immune systems, making them more resistant to diseases and less susceptible to pest infestations. When faced with stress, vigorous crops can recover more efficiently. They might bounce back quicker after a period of drought, heat stress, or other adverse conditions, allowing for a better chance of successful growth and yield [18,148].

Efficient water management through techniques like alternate wetting and drying (AWD) reduces water usage while maintaining or improving yields. AWD helps adaptation to erratic rainfall patterns by allowing farmers to adjust water levels based on plant needs.

Diversifying crops in rotation helps soil fertility maintenance and pest and disease control, and reduces dependence on single-crop cultivation. This practice enhances the resilience of rice farming against climate-induced risks. Furthermore, practices such as organic fertilization and cover cropping improve soil structure and water retention capacity, making fields more resilient to droughts and floods [18,169].

By implementing these agroecological practices, paddy farmers can enhance their resilience to climate change. Water-efficient techniques minimize the impact of changing rainfall patterns, while crop rotation and soil health improvement methods reduce vulnerability to pest outbreaks and enhance overall farm resilience. These strategies collectively improve the adaptability of paddy farming to uncertainties due to climate change in Indonesia.

#### 4.1.3. Mitigation and Adaptation Synergy

Mitigation strategies show their effectiveness within the framework of climate-smart agriculture (CSA). CSA aims to reduce GHG emissions while simultaneously enhancing a system's resilience to climate change, thereby enabling increased crop production or, at the least, maintaining current levels despite climate change [18,172]. Central to CSA is integrated soil health management, such as integrated soil organic matter and nutrient management, which serves to preempt issues associated with climate change and bolster agroecosystem resilience [172]. This approach integrates agricultural development to ensure food security and enable adaptation to climate change. For instance, optimizing nitrogen fertilizer use not only reduces nitrous oxide emissions but also enhances crop resilience against pests and diseases. Another example is alternate wetting and drying, which curtails methane emissions while conserving water for redistribution during dry periods [18,173].

Overall, CSA can be applied to improve and maintain soil health and increase crop production and the resilience of soil ecosystems against the adverse effects of climate change.

### *4.2. Nutrient Recycling*

Agroecological management also optimizes nutrient recycling and organic matter turnover [174]. Nutrient cycling is a vital ecosystem process by which available forms of nutrients move and exchange from the environment into living organisms and are subsequently recycled back into the environment [175]. The cycling of nutrients between soil, plants, and animals is a dynamic and continuous process. Chemical elements such as C, O, H, S, N, and P are essential for life, and their recycling is crucial for sustaining plant growth and yield [175].

Microbes in the soil play a dynamic role in releasing mineral nutrients through organic matter decomposition and mineral recycling. These mineralized nutrients are then absorbed by plant roots along with water, contributing to the creation of new organic material [175]. They are also crucial in maintaining soil structure and quality for sustainable plant growth.

Healthy soil acts as a dynamic living system that delivers multiple ecosystem services. Improved nutrient recycling is one of the important services in agroecological nutrient management [176].

### *4.3. Water Conservation*

Indonesia is blessed with a range of annual rainfall, varying from around 800 mm in East Nusa Tenggara to more than 4000 mm in Sumatra, Java, and Papua (rainfall data can be accessed from BMKG, https://dataonline.bmkg.go.id/home, accessed on 3 January 2023). These substantial rainfall amounts, alongside its water bodies, facilitate both irrigated and rain-fed paddy farming. However, water availability for paddy fields is compromised due to the discontinuity of irrigation networks caused by growing urbanization and industrialization, leading to the damage and discontinuity of irrigation networks [177]. Furthermore, approximately 46% of irrigation systems in Indonesia have deteriorated due to aging infrastructure [177]. Urban and industrial developments near paddy field areas also pose a threat of hazardous chemical contamination [177,178]. Climate change can cause changes in rainfall patterns, including a higher frequency of extreme rainfall, and could further negatively affect water availability and agricultural infrastructure [179], especially in rain-fed areas. However, water-efficient farming practices like alternate wetting and drying (AWD), precision irrigation, and improved water management practices can conserve water in rice cultivation. A review by Ishfaq et al. (2020) concluded that AWD can save between 25% and 70% of water use without reducing yields [180].

### *4.4. Biodiversity Conservation*

The implementation of agroecological nutrient management, as explained in Section 3, emphasizes the importance of using a proper and balanced amount of synthetic fertilizers, enhancing the use of organic fertilizers to compensate for a portion of nutrient requirements, incorporating biofertilizers, and utilizing natural nutrient sources to maintain soil fertility and crop productivity while minimizing environmental impacts. This approach conserves the biodiversity of microorganisms, which significantly contributes to overall ecosystem health, including soil organisms, insects, and various aquatic flora and fauna, such as diverse bird species, amphibians, and aquatic plants.

Moreover, the agroecological nutrient management system promotes beneficial organisms like pollinators and natural predators of pests, thus contributing to biodiversity. Additionally, farming systems and crop rotation, as outlined in Section 3.6, create varied habitats for different species, thereby enhancing overall biodiversity. This diversity includes various bird species like egrets, herons, and ducks, fish, frogs, beneficial insects such as ladybugs and lacewings, a range of aquatic plants, and soil-dwelling organisms like earthworms, beneficial bacteria, and fungi [181].

## 5. Intensification and Control of Paddy Field Conversion

To keep pace with the increasing population, agricultural production needs to be increased [182]. However, many countries are facing problems related to the rapid conversion of paddy fields and insignificant increases in rice yield [14,183], leading to a widening gap between rice need and production. These two problems must be overcome simultaneously to achieve self-sufficiency targets.

Indonesia's paddy field conversion rate, analyzed by high-resolution remote sensing techniques (including IKONOS, QuickBird, or Worldview), is alarming at 96,500 ha year$^{-1}$. If this trend continues, the total paddy field area of 7.46 million ha in 2019 [184] will decrease to around 5.2 million ha by 2045 [16].

The rice yield data from Indonesia's national statistics agency (rice yield data are from the Central Bureau of Statistics, https://bps.go.id, accessed on 10 January 2023) show an average yield increase of 0.04 t ha$^{-1}$ year$^{-1}$, from around 4.4 t ha$^{-1}$ in 1993 to 5.2 t ha$^{-1}$ in 2022. This yield level can further be increased by implementing sustainable intensification to attain a yield of 7.28 t ha$^{-1}$ year$^{-1}$, which is 80% of the yield potential of 9.1 t ha$^{-1}$ [14,185].

To demonstrate the importance of yield increase and the control of land conversion, a two-variable scenario analysis is conducted as follows:

- Rice yield increase scenario:

$Y_{\_BAU}$ = The yield, starting at 5.2 t ha$^{-1}$ in 2022, increases 40 kg ha$^{-1}$ yr$^{-1}$ in accordance with the historical (business as usual, BAU) trend (see the Central Bureau of Statistics for more information, https://bps.go.id, accessed on 10 January 2023).
$Y_{\_80\%}$ = The yield, starting at 5.2 t ha$^{-1}$ in 2022, increases 74 kg ha$^{-1}$ yr$^{-1}$ to attain 80% of the yield potential of 9.1 t ha$^{-1}$ (7.3 t ha$^{-1}$) in 2050 (Yuan et al., 2022) [14].

- Paddy field conversion scenario:

C96.5 = The business-as-usual (BAU) level of paddy field conversion of 96,500 ha year$^{-1}$.
C60 = The medium level of paddy field conversion of 60,000 ha year$^{-1}$.
C30 = The optimistic low level of paddy field conversion of 30,000 ha year$^{-1}$.

The average cropping intensity is fixed at 1.43 (cropping intensity data are from the Central Bureau of Statistics, https://bps.go.id, accessed on 10 January 2023), and the annual per capita consumption is fixed at 110 kg milled rice. Milled rice yield is fixed at 0.576 of the unhusked rice, and population growth is assumed at 0.5% annually, starting from 280 million in 2020 to 322 million in 2050 (milled rice yield data are from the Central Bureau of Statistics, https://bps.go.id, accessed on 10 January 2023). Under the three paddy field conversion scenarios, if the conversion rate is 30,000 ha year$^{-1}$, 60,000 ha year$^{-1}$, or 96,500 ha year$^{-1}$, paddy field area in 2050 will be 6.62, 5.78 or 4.76 Mha, respectively. A summary of the scenarios is presented in Figure 2.

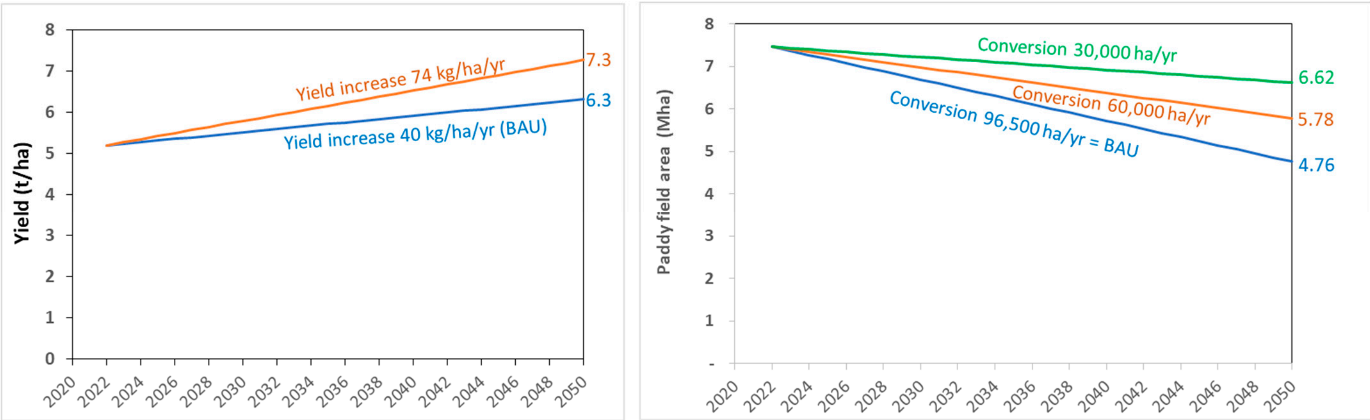


**Figure 2.** Scenarios of yield increase of 40 kg ha$^{-1}$ year$^{-1}$ (business as usual, BAU) and 74 kg ha$^{-1}$ year$^{-1}$ for attaining 80% of the yield potential by 2050, and paddy field conversion rates of 96,500 ha year$^{-1}$ (BAU), 60,000 ha year$^{-1}$ and 30,000 ha year$^{-1}$.

Figure 3 shows the results of the scenario analysis on national rice production and consumption. If the yield increase follows the BAU trend, Indonesia will face a rice deficit in 2041, even if the conversion rate can be kept at no more than 30,000 ha year$^{-1}$. If the conversion rate is 96,500 or 60,000 ha year$^{-1}$, a rice deficit will occur in 2026 or 2028, respectively. Rice self-sufficiency is assured if the annual yield increase is 74 kg ha$^{-1}$ year$^{-1}$ while paddy field conversion is controlled at a maximum of 30,000 ha year$^{-1}$. However, if the paddy field conversion remains at 96,500 or 60,000 ha year$^{-1}$, rice self-sufficiency can only be maintained until 2030 or 2046, respectively.

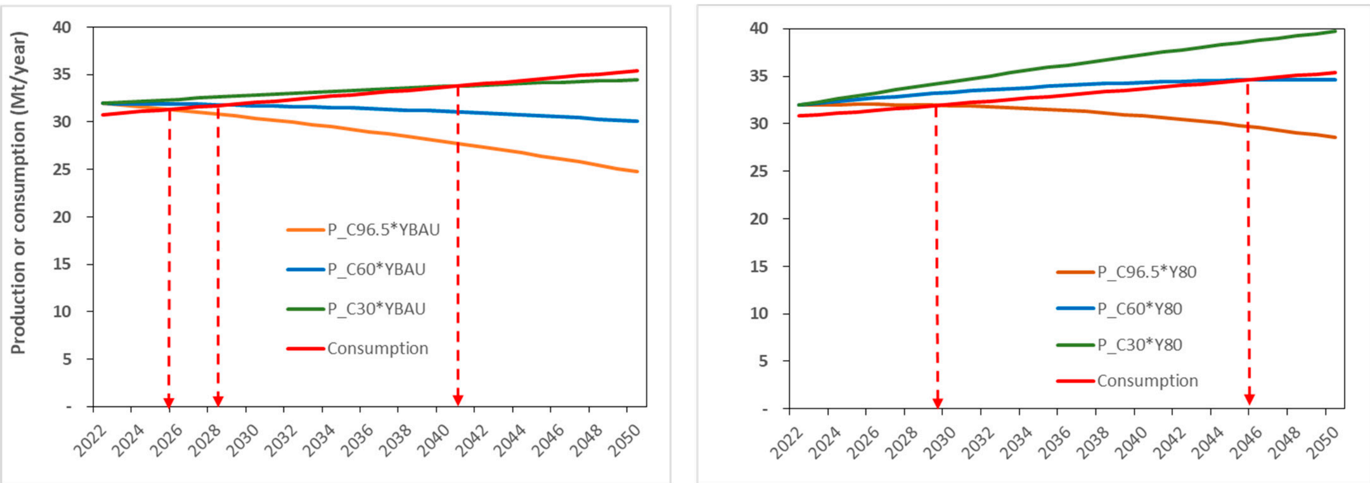


**Figure 3.** Milled rice production and consumption at different land conversion rates and yield increase scenarios. P_C96.5 = milled rice production at paddy field conversion rate of 96,000 ha year$^{-1}$; P_C60 = milled rice production at paddy field conversion rate of 60,000 ha year$^{-1}$; and P_C30 = milled rice production at paddy field conversion rate of 30,000 ha year$^{-1}$. YBAU = rice grain yield increase under the business-as-usual rate of 40 kg ha$^{-1}$ year$^{-1}$; Y80 = rice grain yield increase of 74 kg ha$^{-1}$ for attaining 80% of the yield potential by 2050. * denotes the milled rice production under the combined different conversion and yield increase scenarios. Red dash arrows indicate the year when the consumption equals the production under selected combined scenarios of conversion and yield increase.

This analysis clearly shows that it is crucial to accelerate the yield increase and substantially decrease paddy field conversion to maintain rice self-sufficiency. Controlling paddy field conversion is one of the most difficult challenges to address. It requires inter-ministerial and private sector coordination. The current trend of rapid infrastructural development—which often comes at the expense of highly productive agricultural areas—may be profitable in the short run, but it puts food self-sufficiency, which is the inter-regime's main objective of agricultural development, at high risk.

## 6. Challenges in Implementing Agroecological Management

The implementation of improved management systems that adhere to agroecological principles is challenged by the economic, social, institutional, and technical problems faced by farmers. Table 5 lists examples of agroecological indicators, improved management systems required to address these indicators, implementation challenges, and strategies to overcome these challenges.

Apart from the strategies explained in Table 5, the reality is that high-yielding rice varieties dominate Indonesia's paddy farming. These varieties exhibit high responsiveness to synthetic fertilizer applications, leading farmers to prioritize their use. Consequently, the effects of organic and biofertilizers might be masked by the extensive application of synthetic fertilizers.

However, after acknowledging the beneficial effects of organic fertilizers on soil health, emission reduction, and adaptation to climate change (as discussed in Section 4), it becomes necessary for the government to promote their use. This necessitates the implementation of policies aimed at such promotion, including the following [186–189]:

- Financial incentives in the form of subsidies and/or financial support for farmers transitioning to organic fertilizers.
- Training and extension services to inform farmers about the benefits of organic fertilizers, proper application methods, and their impact on soil health and crop yield.
- Training on techniques to make compost and the use of local nutrient sources.
- Research and development funding aimed at improving the effectiveness and efficient production of organic fertilizers, including on the simpler storage and longer viability of biofertilizers.
- Regulatory support that favors the use of organic fertilizers. This includes setting the standards for organic fertilizers and certification programs to ensure quality.
- Investing in infrastructure such as composting and biochar facilities and organic waste management systems to facilitate the production and distribution of organic fertilizers.
- The establishment of pilot programs at selected farmers' fields to demonstrate the effectiveness of organic fertilizers is essential. These pilots should aim to demonstrate the beneficial effects of organic fertilizers, in addition to showing the ideal combination of synthetic and organic fertilizers.

Implementing a combination of these policies could encourage the adoption and usage of organic fertilizers while reducing dependency on synthetic ones, promoting sustainable agricultural practices in the long run.

Finally, with the increasing price of chemical fertilizers, there should be an increased emphasis on the use of organic, bio-, and bioorganic fertilizers while reducing the reliance on inorganic fertilizers. This shift will lead to more economical and efficient fertilization practices. Furthermore, the enhanced use of organic fertilizers is more environmentally friendly. Farmers should be protected from the overpromotion of certain products lacking proven effectiveness. Finally, nutrient sufficiency should be ensured from the combined use of synthetic and organic fertilizers because yield increase is a must in attaining rice self-sufficiency (see Section 5).

**Table 5.** Examples of agroecological indicators, improved management systems, challenges, and suggested improvements.

| Agroecological Indicator | Improved Management System | Challenges in Implementation | Strategies to Overcome the Challenges |
|---|---|---|---|
| Lower methane ($CH_4$) emissions | Intermittent irrigation, including implementation of the System of Rice Intensification | Water may be excessive when draining is needed or deficient when flooding is needed | Improved irrigation and drainage systems |
| | Use of low $CH_4$ emission varieties | Low-emission varieties may not be the high-yielding or high-quality varieties; hence, they are not preferable | Long-term genetic program to produce low-emission, high-yielding and high-quality rice varieties |
| Lower nitrous oxide ($N_2O$) emissions | Improve efficiency of nitrogen (N) fertilization | Farmers are traditionally happy with quick response of N fertilizers | Improved extension and wider use of leaf color chart for N application efficiency |
| Higher availability of essential nutrients | Use inorganic fertilizers based on local specific or test-kit-assisted recommendations supplemented by organic and natural fertilizers | Unaffordability and/or unavailability of fertilizers at the right amount and the right place | • Regularly update soil nutrient status maps<br>• Explore locally available sources of nutrients<br>• Ensure the availability of chemical fertilizers at the right time, amount, and place, as well as at affordable prices |
| Improved nutrient balance, especially by higher potassium (K) application | Increase application of K from inorganic and organic fertilizers | • High-priced K fertilizers<br>• Need to regularly update nutrient status maps | • Optimize the application of locally available organic matter, especially straw<br>• Explore the use of natural fertilizer such as stonemeal<br>• Shift a portion of the N fertilizer subsidy to K fertilizers |
| Increased soil carbon stock | Application of biochar | • Scarcity of feedstock because of competition with off-farm utilization<br>• Extra work and costs to make biochar | • Explore alternative feedstock<br>• Provide carbon credit |
| | Application of organic fertilizer | Scarcity of feedstock because of off-farm utilization | Optimize the use of other organic fertilizers, such as manure |
| Improved soil health and nutrient availability by microbes | Inoculation of microbes (N fixing, solubilizing, and antagonistic microbes) | Quick expiration of biofertilizers, causing their ineffectiveness | Intensive technical guidance of handling and use of inoculants |

Sources: Adapted from Agus et al. (2022) [18] and Leimona et al. (2015) [189].

## 7. Conclusions and Recommendation

We have outlined Indonesia's challenge in maintaining rice self-sufficiency. This goal hinges on enhancing rice yield, achievable through agroecological nutrient management. Our proposed strategy emphasizes a balanced mix of synthetic, organic, bio-, and bioorganic fertilizers. Improved water management and intercropping and crop rotation further amplify nutrient management success.

Soil tests stand as pivotal indicators for fertilization, yet nutrient dynamics are complex and are influenced by crop uptake and soil reactions. Hence, regular updates of nutrient status maps are vital, and should be complemented by plant tissue tests to fine-tune fertilizer recommendations. Real-time, site-specific advice is enhanced by using soil test kits alongside plant and soil tests. Strategizing potassium fertilizer use through straw recycling, increased subsidies, and exploring alternative sources like stonemeal addresses cost concerns.

Encouraging organic fertilizer usage demands incentives, demonstrations, and stakeholder collaboration to underline their efficacy to farmers. Biofertilizers, which are well-supported in the literature, require promotion through joint efforts among policymakers, researchers, and extension services.

We have also detailed the enhancement of agroecological functions resulting from agroecological nutrient management in paddy farming. These improvements encompass climate change adaptation and mitigation, nutrient cycling, water conservation, and biodiversity preservation. These aspects might be intangible for farmers, thus requiring government policy interventions to bolster the implementation.

Ultimately, agroecological approaches aimed at increasing rice yield must be accompanied by a stringent control of paddy field conversion. Implementing consistent and coordinated measures is imperative to limit the conversion to less than 30,000 hectares per year immediately, while gradually reaching 80% of the yield potential by 2050. Failing to do so will render the rice self-sufficiency objective merely rhetorical.

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