Soil Fertility Evaluation in Long-term Paddy Field on Small Island: A Preliminary Research in Savana Jaya Village, Buru Island, Maluku Province, Indonesia

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Abstract. Efforts to increase rice production continue to face severe challenges, primarily attributed to the declining quality of paddy field soil resources. This study aims to investigate the management of fertilizer utilization and chemical properties of six rice paddy soils in Savana Jaya Village, Waeapo District, Buru Regency. Additionally, it seeks to assess the soil fertility status after 10 to 40 years of continuous rice planting and recommend an approach for fertilizer application. These fields were selected using a purposive sampling method. The soil samples were analyzed total nitrogen (N), potential phosphorus (P), and potential potassium (K) content, as well as cation exchange capacity (CEC). Rice production data was collected by interviewing farmers. The results showed that the soil organic C content and the total N were very low to low, the potential P status was moderate to very high, the potential K status was low to moderate, and the CEC-s of all fields were very low. The soil fertility status of all fields was very low. Organic matter is essential for maintaining the health and fertility of paddy soil, particularly in small islands where the soil is often subjected to intensive use of inorganic fertilizers, posing potential environmental contamination concerns.

1 Introduction

Food security is a global issue, especially in developing countries, including Indonesia. In Indonesia, food is synonymous with rice, although food fulfillment in a broad sense is not limited to the availability of rice in adequate quantities. Therefore, food self-sufficiency to fulfill food security is the most strategic aspect in Indonesia, which has a large population.

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One of the lowland rice areas in Maluku is a transmigration region in Buru Regency. In fact, Buru Regency is frequently seen as a rice silo for Maluku Province. In total, Buru Island has an area of 12,656 km^2. Rice fields are concentrated in just one district, the Waeapo District, with an 8,900 Ha spread along the Waeapo River route [1]. In 2021, the rice production reached 36999.99 tons of dry-milled rice with a harvest area of 8101 Ha. Then, the production decreased in 2022 to 34184.10 from a harvested area of 7375.25 Ha [2].

One of the characteristics of the soil is its ability to provide nutrients. This plays a significant role in the productivity of a paddy field, specifically the major macronutrients, namely N, P, K, secondary macronutrients, and micronutrients. The nutrients can be affected by dynamic and soil genesis, including the biogeochemical cycle. The former refers to the changes in managed agriculture, such as fertilization, straw residue application, tillage, and irrigation. On the other hand, the latter refers to the changes in the soil's order. Physical, chemical, and biological properties affect soil fertility [3]. Proper management can assist in maintaining or enhancing soil fertility, which is essential for agricultural productivity and food security.

The distribution of soil fertility in an area can be determined using land mapping surveys. In addition to defining soil units, this survey also assesses the potential of soil nutrients for plants through laboratory soil analysis. This soil fertility map can be used to develop a soil management model for a specific use and recommend fertilizer use at a particular site [4]. In 2010, Susanto et al. [5] conducted a soil fertility mapping in Waeapu Plain.

Almost all research showed that nutrient management is one of the key determinants of rice yield. However, with inappropriate timing of inorganic fertilizer, higher dosage, and unbalanced application, the impact of lowland rice paddy fertilization on a small island can be significant, especially concerning environmental pollution and degradation. The attainment of a yield target is contingent upon the precise provision of nutrients in the appropriate quantities and timing, aligning with the crop's nutrient demands throughout the growing season. Balanced fertilization means providing the crops with the correct nutrients not supplied sufficiently from indigenous sources [6]. The new paradigm of balanced fertilization combines inorganic and organic fertilizers [7]. More importantly, long-term use of both organic and inorganic fertilisers maintains high levels of bacteria and archaea, which in turn helps keep soil fertility and increase rice yield [8].

Applying inorganic fertilizers to rice plants can enhance the yield of food crops. Nevertheless, the continuous use of chemical fertilizers at high doses can negatively affect the environment and diminish their effectiveness. Excessive inorganic fertilizers can pollute the environment, especially on small islands with limited natural resources and infrastructure. Soil contamination is a significant concern as the excessive use of inorganic fertilizers can accumulate these substances in the soil, deteriorating soil quality. The phenomenon can potentially diminish soil fertility and pose a significant risk to the viability of soil-dwelling species, including earthworms and bacteria. Also, water pollution is a major environmental issue caused by the extensive use of inorganic fertilizers, resulting in the contamination of surface and groundwater sources [9]. The phenomenon can potentially diminish the overall quality of water and pose a significant risk to the viability of various aquatic creatures, including fish and plankton.

Air pollution is a significant environmental concern that can be attributed to the excessive use of inorganic fertilizers. Although the agricultural sector's contribution to carbon dioxide (CO_2) emissions is relatively small, it has a substantial impact on the release of nitrous oxide (N_2O) and methane (CH_4) into the atmosphere [10].

To mitigate the adverse effects of environmental contamination, it is imperative to enhance fertilization efficiency by appropriately managing fertilizers based on plant requirements and land characteristics, hence optimizing production.

Several methods can be employed to enhance the efficiency of fertilization [11-13], such as:

- Utilizing organic fertilizers: The application of organic fertilizers has been discovered to prolong the lifespan of soil organisms and reduce dependence on inorganic fertilizers.
- The Leaf Colour Chart (LCC) utilization in nitrogen (N) fertilization practices has reduced urea fertilizer usage by approximately 15-20% compared to the conventional dosages employed by farmers while maintaining equivalent crop yields.
- Employing appropriate fertilization techniques: The application of fertilizing procedures for rice plants is very subjective and contex- dependent. Determining the precise dosage and timing is challenging due to many influential factors.

Our research objectives were to (1) determine the nutrient status of N, P, and K of paddy soil and (2) compile site-specific NPK rice fertilizer needs based on factors limiting the soil fertility at the research location.

The research findings can be utilized for three purposes: (1) guiding developing site-specific recommendations for fertilizing lowland rice, (2) determining the appropriate dosage of fertilizers for lowland rice based on soil nutrient levels, and (3) enhancing the effectiveness of fertilizer utilization for rice plants. Therefore, the impact on soil and the ecosystem is minimal and not harmful to the environment.

2 Materials and method

2.1 Description of the study area

Savana Jaya village is in the Waeapo sub-district, Buru Regency in Buru Island, Maluku Province, eastern part of Indonesia. The research was conducted from July to November 2022. The condition of the rice field at the time of the study was in a fallow state (resting period after harvesting), so no planting preparation measures, such as tillage and basic fertilizer application, had been taken. The irrigation facility from the Waeapo River is in good condition.

A preliminary survey determined a representative research location following research objectives. Interviews with local farmers were conducted to find out the rice field management system. Based on the interview with 20 farmers about fertilizer use management, including the amount and type of fertilizer, time and method of fertilizer application, and production per planting season (season I and season II), six farmers were involved as representatives. The research location of Savana Jaya village is presented in Figure 1.

To improve their agricultural yields, all farmers in Savana Jaya village use fertilizers. The most commonly used fertilizers are Urea and NPK Ponska, containing 15% N, 10% P_2O_5, 12% K_2O, and 10% S). A few farmers apply organic fertilizer (500 – 1000 kg ha^{-1}) in combination with inorganic fertilizer NPK Phonska and Urea (Table 1).

2.2 Sampling method

This research used a field survey method conducted on six rice fields. Soil sampling was done on each field from 0-20 cm depth and in a composite collected from five subsamples taken diagonally 25 m from the middle point. All the soil samples were air-dried, plant roots and other fragments were removed, and ground by hand to pass a 2-mm aperture sieve. Then, soil samples were analyzed in the soil research laboratory of the Instrument and Fertilizer Standardization Agency in Maros South Sulawesi to determine the chemical properties (pH, organic C, total N, potential P, and potential K, CEC, base saturation) and the soil texture.

Table 1. Land management in six rice farming fields in Savana Jaya village, Buru District

Soil Code	**Area (Ha)**	**Coordinate**	**Duration of land use (years)**	**Amount of fertilizer (kg ha^{-1})**		
				Type	Season 1	Season 2
C1	1	S 03°18’ 530” E127°01’311”	40	Urea NPK Ponska	100 100	100 100
C2	1.5	S 03°18’ 525” E127°01’594”	25	Urea NPK Ponska	150 150	150 150
C3	3	S 03°18’481” E127°01’216”	20	Urea NPK Ponska Petroganik	100 200 500	150 200 500
C4	2.5	S 03°18’ 533” E127°01’163”	26	Urea Ponska	300 150	150 150
C5	3.5	S 03°18’ 517” E127°01’412”	25	Urea NPK Ponska Petroganik	200 200 1000	200 200 1000
C6	1.0	S 03°18’ 512” E127°01’759”	10	Urea NPK Ponska	200 200	200 200

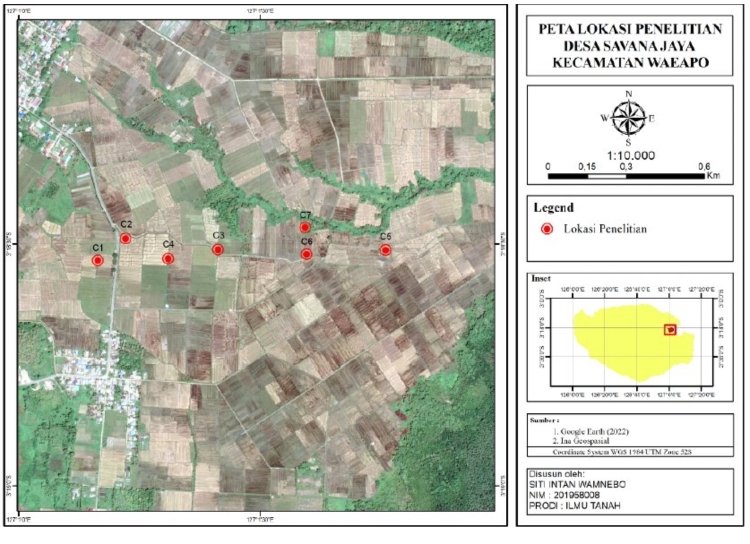

Fig. 1. Map of the six rice fields as a research location in Buru island.

2.3 Chemical analysis

Soil pH was measured using a glass electrode at a soil-water ratio of 1:2.5. The cation exchange capacity (CEC) was determined in 1M NH_4asetat (pH 7.0) solution. The organic Carbon of the sample was quantified by wet oxidation in 1N $K_2Cr_2O_7$ (Walkley and Black method). The soil total N was determined using the Kjeldahl method (Bremner and Mulvaney, 1982). The potential P_2O_5 and K_2O amounts in the soils were extracted in HCl 25%. For soil physical characteristics, the soil texture in 3 fractions (sand, silt, and clay) was done using the pipette method.

2.4 Data analysis

The characteristic criteria of the soil were based on the Indonesian Soil Research Center (1995), as shown in Table 2.

Table 2. Soil chemical characteristics (Soil Research Agency, 1995).

Soil characteristic		**Very low**	**Low**	**Moderate**	**High**	**Very high**
C (%)		< 1.00	1.00-2.00	2.01-3.00	3.01-5.00	>5.00
N (%)		< 0.10	0.10-0.20	0.21-0.50	0.51-0.75	>0.75
C/N		< 5	5 - 10	11 - 15	16 -25	>25
P_2O_5 HCl 25% mg $100g^{-1}$		<15	15-20	21-40	41-60	>60
K_2O HCl 25% mg $100g^{-1}$		<10	10-20	21-40	41-60	>60
CEC ($me100g^{-1}$)		<5	5-16	17-24	25-40	>40
Base Saturation (%)		<20	20-40	41-60	61-80	>80
pH H_2O	Very acid	Acid	Slightly acid	Neutral	Slightly alkaline	Alkaline
	<4.5	4.5-5.5	5.6-6.5	6.6-7.5	7.6-8.5	>8.5

CEC = Cation exchange capacity
BS = Base saturation
This assessment is based solely on general empirical properties.

2.5 Determination of soil fertility status

The soil fertility status of each land unit is determined based on the soil chemical parameters, as outlined by the Soil Research Agency (1995) in Table 3.

2.6 Recommendation for site-specific management

Maps of the P and K nutrients status in paddy fields at a scale of 1:250,000 are available in almost all provinces in Indonesia. This map has been used to compile recommendations for fertilizing paddy fields for specific locations per sub-district. Site-specific balanced fertilizer recommendations are directions for improving soil fertility status by considering the minimum fertile condition combined with adding organic fertilizer. The government established guidelines for the amount of fertilizer recommendations for rice, maize, and soybean crops based on the principle of site-specific balanced fertilization that is efficient and rational [14].

Table 3. Soil chemical characteristics and the soil fertility status determination (Soil Research Agency, 1995)

No	CEC	BS	P_2O_5, K_2O, C-org	Status
1	H	H	≥2 H no L	H
2	H	H	≥2 H with L	M
3	H	H	≥2 M no L	H
4	H	H	≥2 M with L	M
5	H	H	H>M>L	M
6	H	H	≥2 L with H	M
7	H	H	≥2 L with M	L
8	H	M	≥2 H no L	H
9	H	M	≥2 H with L	M
10	H	M	≥2 S	M
11	H	M	Other combinations	L
12	H	L	≥2 H no L	M
13	H	L	≥2 H with L	L
14	H	L	Other combinations	L
15	M	H	≥2 H no L	M
16	M	H	≥2 M no L	M
17	M	H	Other combinations	L
18	M	M	≥2 H no L	M
19	M	M	≥2 M no L	M
20	M	M	Other combinations	L
21	M	L	3 H	M
22	M	L	Other combinations	L
23	L	H	≥2 H no L	M
24	L	H	≥2 H with L	L
25	L	H	≥2 M no L	M
26	L	H	Other combination	L
27	L	M	≥2 H no L	M
28	L	M	Other combinations	L
29	L	L	All combinations	L
30	VL	H/M/L	All combinations	VL

VL Very Low, L Low, M Moderate, H High

3 Results and discussion

3.1 Field condition

The study was carried out in the Savana Jaya irrigated paddy field, the Waeapo flood plain. The altitude of the study area was about 10 m above sea level, and the distance to the nearest coastline is approximately 6.3 km, and to the Waeapo River is 3.6 km.

3.2 Climate in Savana Jaya Village

The Namlea Meteorological Station (2013 – 2022 period) showed that according to the Koppen climate classification, the study area falls within the Awa climate type. The Awa climate type has tropical rain with an average temperature of the coldest month above 18℃

and an average temperature of the hottest month above 22°C. There are one or more months with rainfall of less than 60 mm, and the annual average rainfall is less than 2,500 mm. Rainfall data from the Meteorology station reported that the average monthly rainfall (2013-2022) is 185.04 mm. The total average annual rainfall in the study area is 2220.15 mm. The highest average rainfall occurs in July, namely 315.24 mm, while the lowest average rainfall is observed in October, with 80.74 mm.

3.3 Hydrology and water resources

The Waeapo plain has one major river, namely the Waeapo River, with several tributaries, namely Waegeran, Waetina, Waelo, Waeleman, Waebloi, and Waemiten, which flow from the Southwest to the Northeast and empties into Kayeli Bay – the Banda Sea. Other rivers that empty into the sea are Waelata, Waetele, and Waesanleko. The river has a dendritic structure in its upper section and a meandering pattern in its lower section.

3.4 Physiography

Physiography is a natural formation on the surface of the earth (landform) on a large scale, which is differentiated based on the process of its formation. This physiography closely relates to soil parent material, geological processes, erosion, and sedimentation. Interpretation of satellite imagery with an accuracy of 0.1 ha using the Guide to Landform Classification [15] shows that the study area is divided into two main landform groups, namely 1. Alluvial (A), and 2. Fluvio-Marin (B)

3.5 Geology and parent material

A map at a scale of 1:250,000 by Tjokrosapoetro et al. (1993) showed that the Waeapo is formed from surface sedimentation, divided into two formations, i.e., Alluvium (Qa) and Undak rock.

3.6 Soil type in the study area

The soil in Savana Jaya Village was Inceptisol and Typic Endoaquept. Inceptisol in the Waeapo plains develop from deposits of alluvial material (deposits of clay, sand, and their mixtures) and tertiary sediments consisting of skis and mica, spread over alluvial plains and fluvio-marine landforms. The soil is formed from alluvium sedimentary materials, namely loam and sand, whose development is affected by groundwater and obstructed drainage. Endoaquept soil has an effective depth of less than 100 cm, a gray to light gray soil color, and soil texture classified as silty loam to clayey loam. Soil pH is acidic to slightly acidic (pH 4.5-6.5) [11].

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Table 4. Soil nutrients in six rice paddy field sites in Savana Jaya Village, Buru Island, before planting season II (2022).

Sample	**Texture**	**C-org (%)***	**Total N (%)**	**C/N**	**pH (H_2O)**	**Potential-P (HCl 25%) (mg $100g^{-1}$)**	**Potential-K (HCl 25%) (mg $100g^{-1}$)**	**CEC (me $100g^{-1}$)**	**BS (%)**	**Yield (ton ha^{-1})**
C1	Silty loam	1.22 (L)	0.09 (vL)	13.6	5.20 (acid)	30 (M)	10 (L)	3.48 (vL)	64 (H)	3.85
C2	Silty loam	1.20 (L)	0.10 (L)	12.0	5.32 (acid)	31 (M)	13 (L)	3.69 (vL)	70 (H)	4.13
C3	Silty loam	1.29 (L)	0.10 (L)	12.9	5.82 (s.acid)	38 (M)	13 (L)	3.48 (vL)	83 (vH)	4.27
C4	Silty loam	1.26 (L)	0.12 (L)	10.5	6.64 (neutral)	68 (vH)	30 (M)	3.70 (vL)	56 (M)	4.30
C5	Loam	1.24 (L)	0.09 (vL)	13.8	6.03 (s. acid)	23 (M)	12 (L)	2.82 (vL)	100 (vH)	4.40
C6	Silty loam	0.97 (vL)	0.12 (L)	8.1	5.96 (s. acid)	27 (M)	13 (L)	3.58 (vL)	95 (vH)	4.40

*Criteria according to Soil Research Agency (1995)

vL very Low; L Low, s.acid slightly acid; M Moderate, H High; vH very high

The soil texture, which is dominated by silt and sand (silty loam), reveals that the soils at the research site generally have physical soil restrictions in the form of coarse texture, thin tillage layer, and low water holding capacity. The loamy texture (site C5) is categorized as medium, limiting its capacity to retain nutrients compared to fine-textured soils with more clay particles. The continued rice cropping can cause significant soil nutrient depletion. Dou et al. [16] reported that soil texture is one of the physical characteristics determining rice production. Averaged across cultivars and water regimens, the grain yield of clay soil was 46% greater than that of sandy loam soil. In our study, this problem is worsened by most farmers in Savana Jaya, who burn straw before tilling the field for subsequent planting. Burning straw has the potential to increase greenhouse gas emissions, as well as a negative impact on the soil biota, leading to a decrease in the physical and chemical qualities of the soil.

Soil pH is a significant indicator of soil health. Rice paddy soil can have varying pH levels depending on the location and soil characteristics. The pH of soils was measured using air-dried samples, ranging from 5.20 (acid) in site C1 to 6.64 (neutral) in C4 (Table 4). Relevant to the pH value, the potential P and K were higher in site C4 than in other sites. Furthermore, Ding et al. [17] found from the modeling study that the soil pH values determined in the laboratory changed after flooding. During the period of flooding, the pH of soils with an initial pH below 6.5 increased to an average of nearly 7.0. For soils with an initial pH above 6.5, the pH declined from 1 day to 30 days and subsequently increased to approximately 7.0 on average.

Table 4 shows that at the study site, C-organic ranged from 0.97% (very low) to 1.29% (low). The low C-organic could be due to the continuous rice cropping for Season 1 and Season 2 with intensive chemical fertilization application without returning crop residue organic matter to cultivated land, such as composted straw or composted manure, causing the organic C depletion. This low organic C content can be increased to 80% by adding organic material to the soil. The amount of organic material added to improve soil fertility is ideally 20 t ha^{-1} [18],[19]. The calculation findings indicate that the amount of organic material that can be amended in these rice fields ranges from 13.55-15.15 t ha^{-1}.

The low organic carbon content in rice paddy soil on small islands can have several effects. It can decrease soil fertility and nutrient availability, as organic C and total N play important roles in soil physicochemical fertility. Wibowo and Kasno [20] found a strong positive correlation between soil organic carbon content and total nitrogen in Java Island paddy soils. The linear regression showed that the higher the soil organic carbon content, the higher its ability to retain nitrogen. Soil fertility, especially the nitrogen availability in the soil, can be managed by maintaining the soil organic matter content. During organic matter decomposition, the organic nitrogen undergoes mineralization, whereas the mineral nitrogen becomes immobilized. The long-term effects of the application of organic manure plus straw resulted in a substantial increase in the soil organic carbon (SOC) content of the topsoil (0–10 cm) compared to the use of chemical fertilizers alone [21]. The organic carbon content in the paddy soil ecosystem remained steady over the long-term use of fertilizers and continuous cropping. In our present study, the C/N ratio varied from 8.1 in C6 to 13.8 in C5, indicating that the soil organic matter in field C6 (10-year paddy soil) is more decomposed, probably initiated by mineral fertilization (no organic fertilization).

The parameters of the crop production function are greatly influenced by soil fertility. The N total was very low to low in these study sites. Crop harvesting and leaching can result in the loss of some elements, including N. The fertilization method affects efficiency. Urea fertilizer is usually applied by broadcasting. Utilizing N fertilization by incorporating it into the soil or the reduction layer in paddy field soil is an effort to reduce N loss through ammonia (NH_3) volatilization or drain out of the growth environment [6]. Fageria & Virupax

[22] stated that N is a key factor and the most expensive production input in paddy rice, and if its use is not appropriate, it will pollute groundwater.

The study sites contained low K-potential. Approximately 80% of the potassium (K) in the soil is taken up by the rice crop and stored in the straw. Therefore, it is recommended that the straw be returned to the paddy field.

Savana Jaya soils have mostly moderate P-potential levels. Only in the C4 site was the K-potential level moderate, and the P-potential level was very high. In a previous study by Siregar and Marzuki [11] in Waelo village, Waeapo plain, Buru Island, the application of N and K fertilizers resulted in the most significant absorption of nitrogen by the plants, which was comparable to the plots treated with NPK fertilizers. The amounts of organic C, total N, total P, and total K in the Waelo soil were low, but available P was moderate, and the soil had a clay texture. Rice productivity is considerably enhanced by sufficient available soil K and N. Continuous fertilization with inorganic fertilizer causes a nutrient imbalance in the soil, resulting in a decline in soil fertility. The results of this study encourage farmers to employ optimally balanced fertilizer recommendations that incorporate bio-inputs such as straw compost, biochar straw, and composted manure to improve soil health and increase crop yields.

Nakao et al. [23] and Yanai et al. [9] reviewed that the levels of Nitrogen (N), Phosphorus (P), and Potassium (K) in soils of tropical Asia (Thailand, Philippines, Malaysia) were lower than compared to temperate soils. This discrepancy can be attributed to the relatively intensive weathering of soil minerals due to the warm and humid climate and the relatively low levels of past fertilizer application in tropical regions.

The cation exchange capacity (CEC) is an indicator of soil fertility. The CEC of the paddy soil in this study site is 100% very low, with a value of 2.82 – 3.70 me $100g^{-1}$. The research sites exhibited a significantly low cation exchange capacity (CEC) due to the small proportion of clay content and soil organic matter, indicating its limited capacity to retain and supply essential nutrients required by rice plants. All soil fertility status in investigated areas with and without organic fertilizer is very low. That means the added organic fertilizer was insufficient to increase the C content. Felix et al. [24] reported that the high and low CEC values are related to the C-organic content. The higher the C-organic content, the higher the CEC value; conversely, the lower the C-organic content, the lower the CEC value. Based on the rice fertilization recommendation from the Ministry of Agriculture [14], after harvesting rice using a combined harvester, the straw returns naturally at least 1/3 of the weight of the harvested straw.

Chen et al. [25] found that applying a combination of chemical and organic fertilizers, such as manure (MCF), especially at a ratio of 70% organic to 30% chemical, resulted in consistently high rice yields and enhanced various soil properties. After 32 years of rice farming, many enhancements were seen, such as elevated soil organic matter (SOM) levels, 1 N NaOH-hydrolyzed N, Olsen phosphorus, microbial biomass, and bacterial diversity. Additionally, the issue of soil acidification was mitigated. To overcome the limiting factors in our study (low CEC, inefficient use of inorganic fertilizers), enhancing the level of organic matter through continuous application of manure, compost, or any other mechanisms that can be integrated with chemical fertilizers. Recent microalgae-based biofertilizer experiments were conducted to improve crop yield and soil health, an alternative solution to sustainable agriculture [26][27]. Microalgae have emerged as a viable and environmentally friendly substitute for agrochemicals in agriculture. They offer many advantages, including improving soil fertility, optimizing nutrient management, and decreasing dependence on inorganic fertilizers. Microalgae have exhibited proficient capabilities in nutrient cycling, effectively absorbing and transforming vital elements, including nitrogen, phosphorus, and potassium, into readily accessible forms for plants. Moreover, these organisms can synthesize bioactive compounds, such as phytohormones, that directly influence the physiological mechanisms of plants, facilitating their growth.

Dry-milled rice grain production at the research location ranged from 3.85 to 4.4 tons/ha. This production is below, although not far different from the average rice production in Maluku, which is around 4.5–4.6 tons/ha in 2022 [2]. However, the productivity from Savana Jaya is still low compared to the national productivity of 5.238 tons of dry-milled rice ha^{-1} [2]. In this case, the soil fertility of the paddy fields in Savanah Jaya village determines the low rice production in the research location.

4 Recommendations

According to the Research and Development section of the Indonesia Agriculture Department [14], the calculation of nitrogen fertilizer dose for paddy soil should be based on the productivity level of lowland rice. At low productivity levels (<5t/ha), 200 kg/ha of Urea is needed. At moderate productivity levels (5-6 t/ha), 250-300 kg/ha of Urea is required. While the level of productivity is high (> 6 t/ha), it requires 300-400 kg/ha of Urea. Further, the emergence of a leveling-off in rice productivity in intensive paddy fields is attributed to causes such as the plateauing of yield improvements in new varieties, climate variability, and the impact of climate change. In addition to issues with nutrient balance and low soil organic matter levels, the management of additional nutrients is required. These nutrients include the beneficial element Silica, secondary macronutrients sulfur, calcium, and magnesium, and micronutrients iron, copper, manganese, zinc, and boron. Returning the straw to the paddy field will contribute potassium nutrients and trace elements such as iron, copper, zinc, manganese, boron, and silicon.

5 Conclusions

The paddy soils at the research locations have a low to very low nutrient status for N, with levels ranging from 0.12% to 0.09%. The potential P levels are medium to very high, ranging from 23 to 68 mg per 100g of soil. The potential K is low to medium, ranging from 10 to 30 mg per 100g of soil. Additionally, the cation exchange capacity is very low. Nutrients availability for rice plants is limited by some factors, including organic carbon (C) and cation exchange capacity (CEC). The soil fertility status of all long-term rice fields in this study is very low.

Balanced fertilizer management must be employed through site-specific nutrient management to maintain soil fertility in the research site, namely, combining Urea and NPK compound fertilizer according to soil nutrient status and plant needs while applying organic fertilizers around 13.5 to 15.1 ton ha^{-1} to improve the quality of the soils.

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