



Spatial Assessment of Soil Fertility Degradation and Ecological Restoration Strategies for Sustainable Paddy Agroecosystems Planning in Konawe Regency, Southeast Sulawesi, Indonesia

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<https://doi.org/10.18280/ijdne.210305>

ABSTRACT

Received: 12 January 2026

Revised: 28 February 2026

Accepted: 27 March 2026

Available online: 31 March 2026

Keywords:

agricultural planning, ecological engineering, Konawe Regency, spatial analysis, soil restoration, sustainability of paddy agroecosystems

There have been considerable fluctuations in lowland rice cultivation in the Konawe Regency, Southeast Sulawesi, in relation to soil fertility decline. The main objective of this study is to analyze the spatial pattern of soil fertility degradation in paddy soils and design strategies for soil rehabilitation based on ecological engineering. Sampling for the field work took place from February to June 2025 at 204 points in the major rice-growing areas. The investigation entailed measuring soil chemical properties, such as pH, soil organic carbon (SOC), total N, available P, and K content using standard analytical methods. Spatial distribution of the parameters was carried out using GIS technology based on Inverse Distance Weighting (IDW) interpolation. As a result, over 70% of the paddy soils revealed acidity ($\text{pH} < 5.5$), whereas SOC was low ($< 2\%$) in many major rice-producing areas. N and P nutrients were in the moderate and high categories, while K had moderate and low concentrations, indicating nutrient imbalance under the acidic soil conditions. All the above-mentioned soil constraints decrease fertilizer efficiency. Based on the obtained results, different strategies for rehabilitation of the soils were worked out; includes liming (0.5-3.0 tons per ha), increasing organic matter input in the form of compost, rice straw, and appropriate fertilization. This integrated approach can ensure improvement in the soil functions and increase the efficiency of the nutrients, which can be used as a basis for planning the development of sustainable paddy agroecosystems in Konawe Regency.

1. INTRODUCTION

Rice is one of the world's primary staple foods commodities. It is estimated that almost half of the world's population consumes rice daily [1]. Indonesia ranks among the top countries in terms of rice consumption. The average annual consumption of rice in Indonesia is about 133.15 kg per capita [2]. This quantity is expected to rise further along with the rise in population. Hence, rice is critical for securing food security for the future.

Konawe Regency in Southeast Sulawesi Province is a prominent producer of rice that helps to secure food in the region [3]. In recent years, rice production in Konawe Regency has been hampered by various issues. This is apparent from the reduced land planted and the volatility in rice production levels. For instance, rice production was 188,385 tons of milled dry grain in 2018; fell to 177,444.6 tons in 2019; and rose to 198,280 tons in 2020. Thereafter, rice production fell drastically in 2021-2022 to reach a low of 132,209 tons of milled dry grain. Production rose slightly to 151,058 tons of

milled dry grain in 2023 but was still lower than at the onset of the study period [4].

In addition to that, the decrease in rice production is aligned with the decrease in harvested area. The harvested area stood at 46,364.11 ha in 2019 before gradually declining to 38,277.50 ha in 2023. Specifically, in 2022, the harvested area experienced a decline of 23.48%, while production declined by 23.95%. This clearly implies that the local food production system is under a significant amount of pressure. Despite an increase of 10.86% in harvested area and production in 2023, the rice farming system in Konawe Regency is highly susceptible to disruptions.

Several factors affect the level of rice production, such as climate change, availability of irrigation water, pressure from pests and diseases, and land management. Nevertheless, the notable reduction in the level of production indicates some internal issues, specifically those related to soil fertility [5]. Typically, paddy soils tend to be acidic and have low levels of soil organic carbon (SOC) alongside nutrient imbalance [6]. These issues imply that the efficacy of fertilizers is relatively

low, hence affecting yield stability.

Moreover, the pH of soil serves as a regulator affecting the availability of nutrients and fertilizer efficiency [7, 8]. SOC constitutes another vital component responsible for biological processes and soil nutrient retention capacity [9]. Thus, reduction of both soil pH and organic carbon content shows a poor state of the agroecosystem functions that cannot be compensated for with increasing fertilizer applications [10, 11]. Such a state can account for the lack of a direct correlation between production input increases and yield improvements and is one of the reasons for yield variations in rice in Konawe Regency.

The issue of soil acidification is well-known in agriculture and affects paddy productivity in the tropics. In conditions of acidity ($\text{pH} < 5.5$), the availability of phosphorus decreases; additionally, phytotoxicity due to high levels of Al^{3+} prevents root formation and nutrient acquisition, leading to low rice yields [7, 8]. The problem is universal, as evidenced by many studies conducted in different tropical countries. Sub-Saharan research on acidity in rice fields showed that the penalty of yield reached 20-50% due to uncontrolled aluminum toxicity in acidic soils [12]. Similarly, in South and Southeast Asian countries, including Thailand, Vietnam, and Malaysia, intensive fertilization and heavy rain cause soil acidification, resulting in low paddy yield and low nitrogen use efficiency [13, 14]. Hence, it becomes obvious that the relationship between soil acidity and rice productivity is global and inherent to tropical agroecosystems and should not be neglected while considering the case of Konawe Regency.

The use of principles of ecological engineering enables

creating an adaptive concept to increase sustainability by restoring functions and processes of an agroecosystem and increasing resistance to environmental stresses, which results in stable rice productivity in the future [15, 16]. Such practices as liming [17], balanced fertilization, application of organic materials, and using rice straw in the area can substantially increase the resistance of rice production to environmental stresses and make yields stable [18]. Still, to create effective strategies, it is vital to know more about spatial soil fertility patterns and relations with rice productivity dynamics in the area.

Thus, this study aimed to assess the fertility state of soils in Konawe Regency through their chemical soil characteristics and develop a strategy for management based on ecological engineering principles to restore soil functions and ensure rice productivity.

2. MATERIAL AND METHOD

2.1 Study area

This study was conducted in rice paddy fields in Konawe Regency, Southeast Sulawesi Province, Indonesia (Figure 1), from February to June 2025. The study combined soil survey, laboratory analysis, and GIS mapping approaches to study the spatial distribution of soil fertility decline and to create ecological restoration measures for the rice agroecosystem in the region.

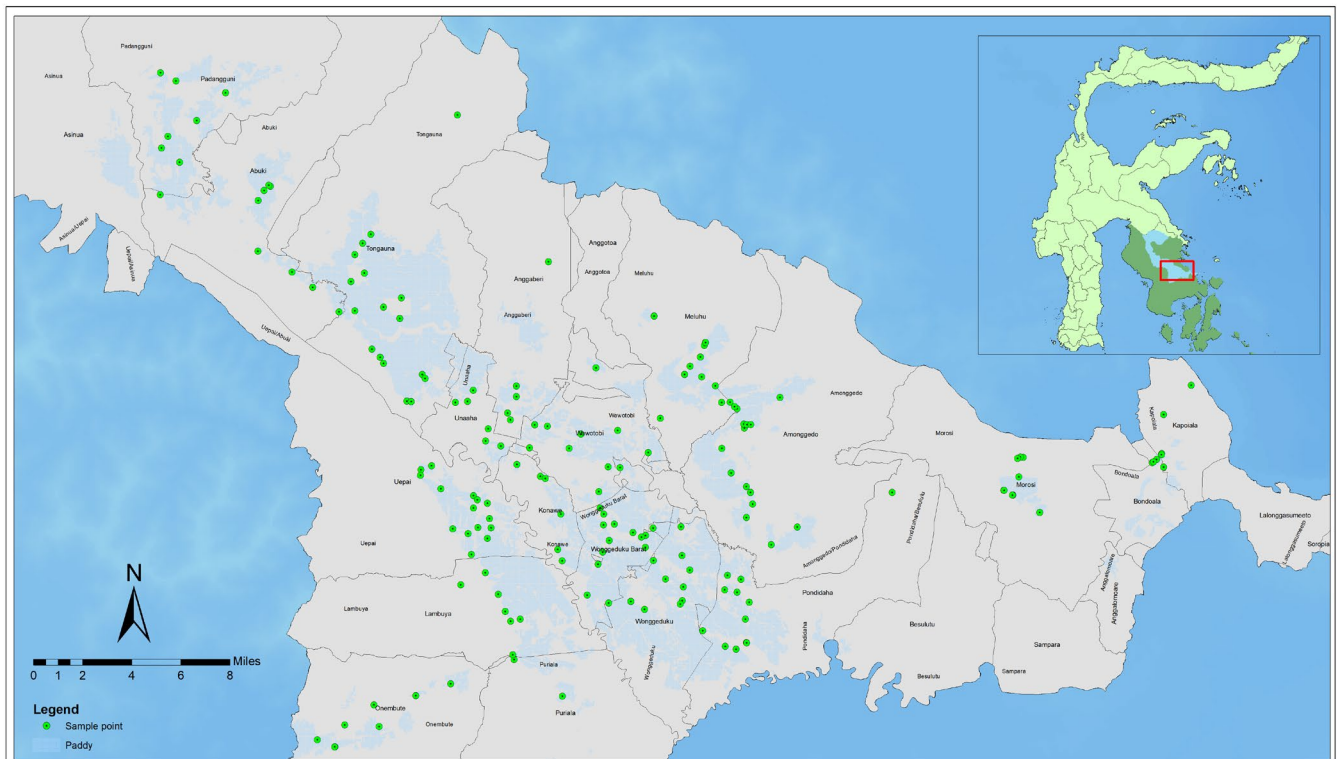


Figure 1. Study site

2.2 Soil sampling

Samples were collected from 204 sampling points representing the spatial distribution of rice agricultural areas

in this region. Soil sampling was conducted as described by research [19] using a soil auger (2.5 cm diameter) to a depth of 0–20 cm. The soil samples, then, were dried, powdered, and sieved at 2 mm.

2.3 Soil chemical analysis

Chemical analysis of soils was carried out in the Soil Laboratory of the Faculty of Agriculture, Halu Oleo University. The analysis was conducted based on the methods of chemical analysis of soils, plants, and fertilizers according to the norms of the Testing Center of the Instrument of Agricultural Land Resources of the Indonesian Ministry of Agriculture [20].

2.4 Soil pH

The soil pH was determined using a pH meter after making a soil water extract at a ratio of 1:2.5 (soil/H₂O). The suspension was agitated for 30 min and allowed to equilibrate before measurement. The pH meter was calibrated with buffer solutions of pH 7.0 and pH 4. The results obtained were then grouped according to Table 1.

Table 1. Classification of soil pH (H₂O)

Parameter	pH (H ₂ O)
Very acidic	< 4.5
Acidic	4.5-5.5
Slightly acidic	5.5-6.5
Neutral	6.6-7.5
Slightly alkaline	7.6-8.5
Alkaline	> 8.5

2.5 Soil organic carbon

The method used to determine SOC was the Walkley-Black method. This method involved the weighing of 0.500 g of a soil sample that had been sieved to 0.5 mm onto a reaction flask. Afterward, the 2 N K₂Cr₂O₇ solution and concentrated H₂SO₄ were added to the soil sample and oxidized. Thereafter, the suspension was diluted to its needed volume and left to settle, whereupon the absorbance of the supernatant was read on a spectrophotometer at 587 nm.

2.6 Total nitrogen

The total nitrogen (N) was determined via the Kjeldahl method. The soil sample was mixed with concentrated H₂SO₄ and catalysts to form (NH₄)₂SO₄ after digestion. This process involved heating up the sample to about 350 °C for 3-4 h or until the extract became clear. Thereafter, the resulting mixture was diluted to its needed volume and left to stand to allow sedimentation of the suspended particles. Indophenol blue formation was measured using absorbance at 660 nm.

2.7 Phosphorus

Determination of P content was conducted through the Bray

extraction procedure. Soil samples were subjected to an extraction procedure using the Bray solution, and the color development procedure was done by adding phosphate color-forming reagent to the filtrate obtained from the Bray extraction procedure. Absorbance reading was obtained at a wavelength of 889 nm using the spectrophotometer.

2.8 Potassium

Determination of potassium (K) content was achieved using 25% HCl extract. K concentration was analyzed using an Atomic Absorption Spectrophotometer (AAS). A calibration standard curve was used for the determination.

Classifications of SOC, total nitrogen, available phosphorus, and potassium levels were conducted based on their measured concentrations (Table 2).

2.9 Spatial analysis

The spatial distribution of soil fertility parameters was analyzed using a GIS. A total of 204 sampling points were used to represent the spatial variability of soil properties across the study area. The sampling density of approximately one point per 1.5-2.0 ha of active rice cultivation area was determined to adequately capture the spatial heterogeneity of soil properties, given the diversity of management zones, soil types (Ultisols and Inceptisols), and topographic conditions in the region. This density is consistent with recommended practice for site-specific nutrient management in tropical lowland rice systems [21]. The Inverse Distance Weighting (IDW) interpolation method was applied to estimate soil parameter values at unsampled locations. In this method, the weights assigned to neighboring points are inversely proportional to their distance from the prediction location, such that closer observations exert a stronger influence on the estimated values [21]. IDW interpolation was implemented using a power parameter of $p = 2$, which was selected based on preliminary sensitivity analysis comparing p values of 1, 2, and 3. A fixed search radius incorporating the 12 nearest neighboring points was applied uniformly across all soil properties. To evaluate interpolation accuracy, leave-one-out cross-validation was performed for each soil parameter. The root mean square error (RMSE) values obtained were: pH = 0.28 pH units, SOC = 0.18%, total N = 0.04%, available P = 1.2 ppm, and K = 3.4 mg/100 g. The above-mentioned values can be considered satisfactory for site-specific soil fertility mapping of tropical rice fields and demonstrate sufficient accuracy of interpolation of soils in the study area.

The interpolated surfaces were subsequently classified into soil fertility status and soil reaction classes based on predefined classification thresholds (Tables 1 and 2). These spatial analyses were used to identify patterns of soil fertility degradation and to determine priority areas for ecological restoration within rice agroecosystems.

Table 2. Classification of soil fertility status based on C, N, P, and K

Soil Parameter	Very Low	Low	Moderate	High	Very High
C (%)	< 1	1-2	2-3	3-5	> 5
N (%)	< 0.1	0.1-0.2	0.21-0.5	0.51-0.75	> 0.75
Bray-1 P (ppm P)	< 4	5-7	8-10	11-15	> 15
K ₂ O HCl 25% (mg/100 g)	< 10	10-20	21-40	41-60	> 60

2.10 Restoration strategy

The restoration strategy involves the identification of the dominant constraining factors related to soil acidity and insufficient organic matter content, as well as soil nitrogen (N), phosphorus (P), and potassium (K) status of soil fertility. Based on the analysis of constraints, the following recommendations have been suggested for the improvement of soil conditions in the studied rice ecosystems.

3. RESULTS AND DISCUSSION

3.1 Spatial distribution of soil pH

Soil pH is a measure of the amount of hydrogen ions (H^+) in the soil. It indicates the chemical status of soil that decides acidity or alkalinity. The pH scale is 0-14, with 7 being neutral soil [22]. The results of soil pH tests on paddy fields in Konawe Regency indicate that the acidity of the land varies and may be classified as Neutral, Slightly Acidic, and Acidic. Most of the soils in the research region are either somewhat acidic or acidic. Only a few villages like Pondidaha and West Wongeduku have neutral soils.

For rice plant growth, a slightly acidic pH of soil (5.5-6.5) in paddy soils is still conducive, as minerals such as phosphorus, potassium, calcium, and magnesium are still available [23]. However, highly acidic soils ($pH < 5.5$) reduce nutrient availability and increase the solubility of Al^{3+} and Fe^{2+} ions, which hinder plant growth [24]; the detailed fixation process will be discussed in the discussion section.

Factors that affect soil acidity in the study area include

excessive rainfall resulting in leaching of soil bases, high use of nitrogen-based fertilizers, and imbalanced nutrient management practices [25]. Also, the presence of Ultisol and Inceptisol soils promotes soil acidity due to leaching processes occurring over an extended period of time.

In some areas with neutral soils, the local geology and better land management practices, such as liming, help. The above data imply that soil pH is one of the key elements impacting the quality of paddy soils in Konawe Regency and needs to be successfully maintained by balanced fertilization, addition of organic material, and liming.

Figure 2 below shows that acidic soil was the main occurrence in many areas of rice growing, and only small areas with neutral pH were found in the Pondidaha and West Wongeduku Districts. So the acidity of the soil is a universal problem and not a specialized concern. The presence of spatial clusters of very acidic soils ($pH < 5.0$) in the southern and eastern subdistricts is associated with the dominance of Ultisol soil profile properties. This suggests that the soils are extremely worn, inadequately base-saturated, and excessively saturated with aluminium. The intensive rice culture without regular liming is gradually removing the soils of important base ions such as Ca^{2+} , Mg^{2+} , and K^+ by crop removal and leaching. However, the minor neutrality of the soils in the Pondidaha and the West Wongeduku Districts is not only dictated by the geological features but also by the lime application in agriculture by the local farmers in these locations. This distinction has evident managerial ramifications as acidic zones should be prioritized for lime treatment first to restore fertility conditions, as phosphorus will stay unavailable and aluminium toxicity will persist no matter what amount of fertilizers will be utilized otherwise.

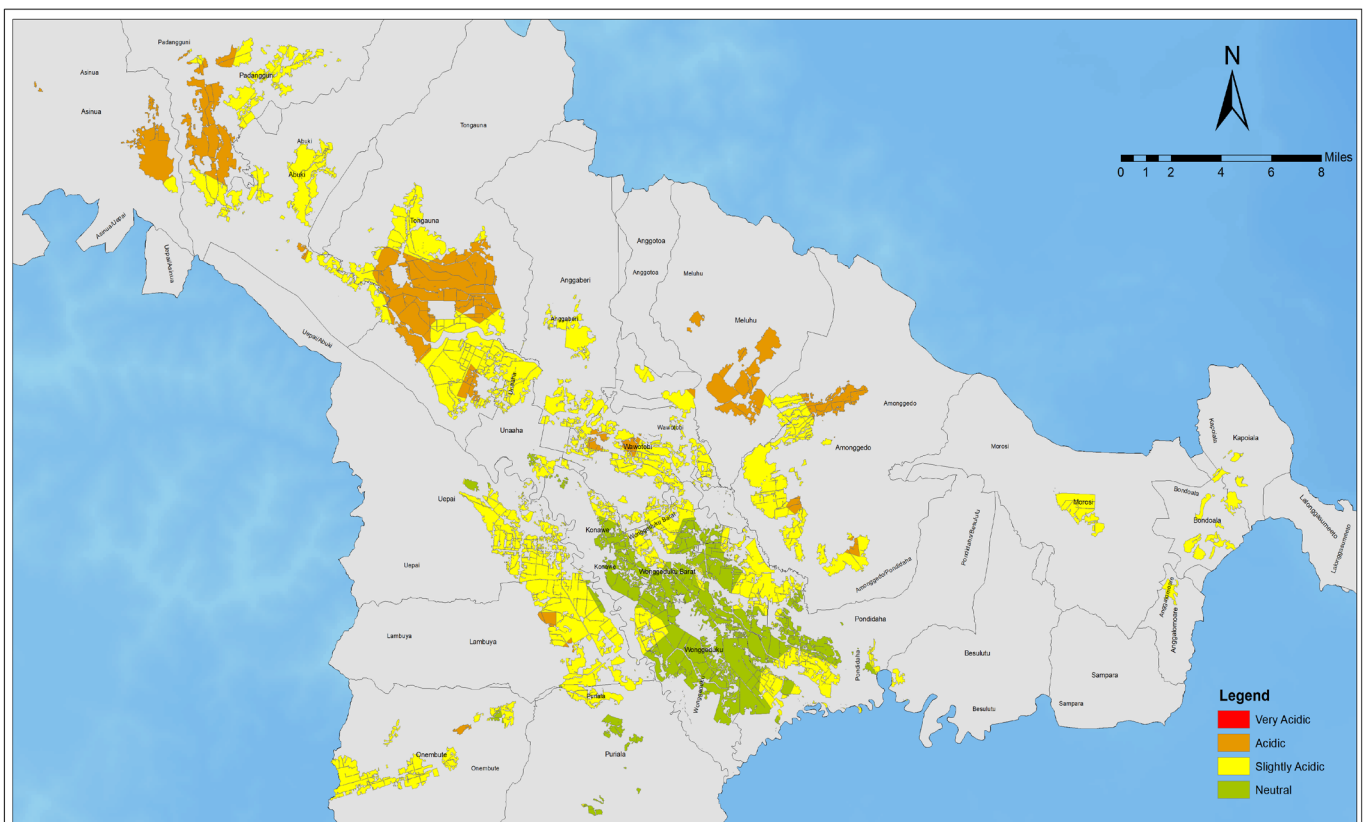


Figure 2. Spatial distribution of soil pH in paddy agroecosystem of Konawe Regency, Southeast Sulawesi

including coastal agriculture territories of Kalimantan in Indonesia [32]. In general, the persistent potassium insufficiency revealed in all the examined soils is worth considering separately. Potassium insufficiency is common in highly weathered tropical soils of the Ultisolic class, as their cation exchange capability is characterized by a domination of the variable charge clays, such as kaolinites, whose intrinsic adsorption potential for K^+ ions is not very strong. As a result, with the prevailing climate conditions (precipitation amounting to 1.800-2.500 mm per year), K^+ ions in these soils are very mobile and easily move down into the subsoil with each irrigation/flooding event due to the absence of retention in soils of the examined region characterized by a low proportion of clay minerals and low organic matter concentration. Such a process is additionally enhanced due to the predominant application of nitrogen-based fertilizers, as the rice farmers of the Konawe region use urea and SP-36 based on governmental recommendations, yet do not use potassium chloride or apply this fertilizer insufficiently, considering it less important compared to others. In this way, as a result of each cropping season, potassium mining continues because crops remove much more potassium than soils obtain. Internationally recognized evidence testifies to the same pattern as in Vietnam and Thailand, tropical rice paddies, potassium deficiency is usually the first nutrient

constraint limiting the yields, while nitrogen and phosphorus have always been used predominantly [14, 33]. Thus, addressing the issue of soil potassium depletion via additional potassium chloride application (up to 60-90 kg K_2O ha^{-1}) should be considered together with the improvement of soil acidity problems in K- deficient soils.

3.4 Restoration of lowland rice farming land

3.4.1 Liming

Lime application is considered one of the key practices for management of acidic soils since it increases pH, improves soil conditions, and enhances the availability of nutrients to rice plants [34]. Agricultural lime, such as calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$), can be used for liming. This approach decreases the solubility of toxic ions such as aluminum (Al) and iron (Fe), reduces soil acidity, and improves the usage of fertilizers, notably phosphorus and potassium fertilizers [35].

Based on the findings, it can be stated that the recommended liming dose for paddy fields in the Konawe Regency was 0.5-3.0 tons ha^{-1} , depending on soil acidity. On soils with low pH values, a larger amount of lime is required to achieve a nearly neutral soil.

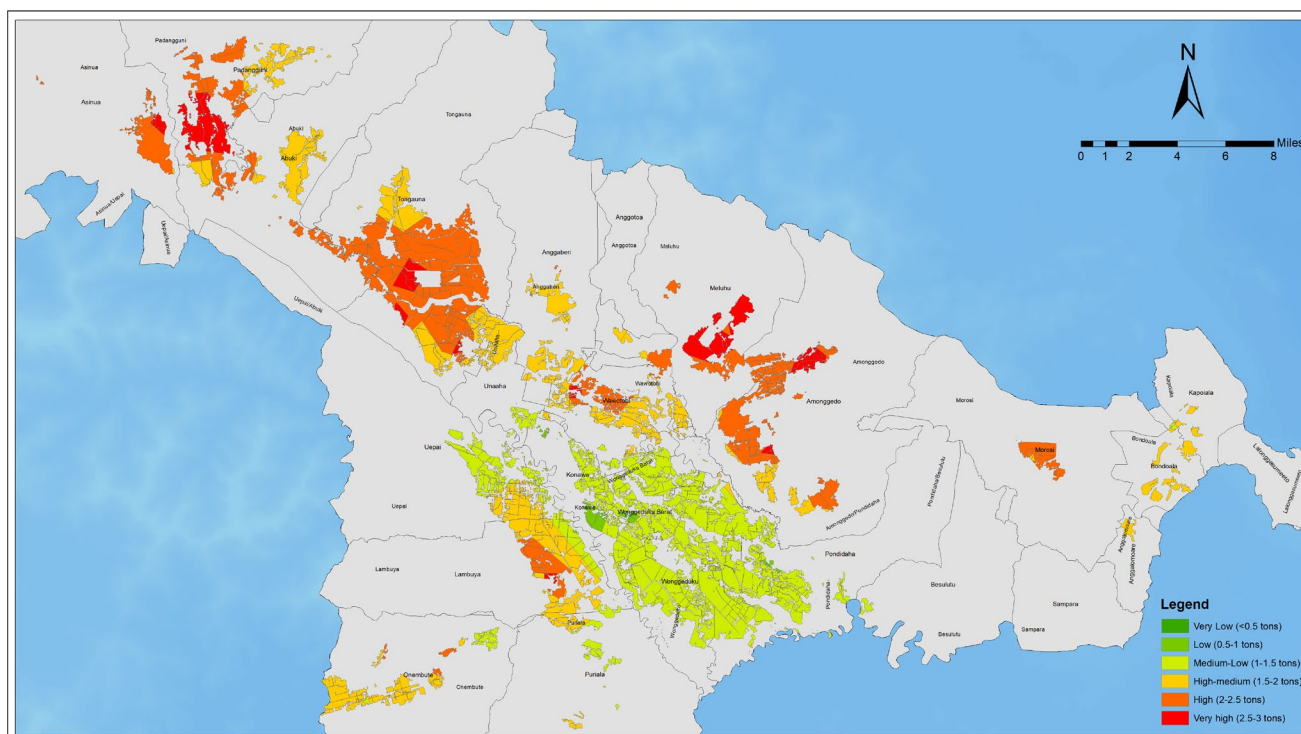


Figure 4. Spatial distribution of recommended lime application rates for paddy agroecosystem in Konawe Regency, Southeast Sulawesi

Figure 4 illustrates the regional distribution of recommended rates of lime application to paddy soils of Konawe Regency. The difference in soil properties and high-priority zones requiring intervention for improvement of soil properties were the reasons for regional variability in lime needs. In paddy soils with high rainfall and highly cultivated locations, there are larger losses of soil base cations, resulting in higher levels of soil acidity [14].

The use of lime at prescribed rates will stimulate root growth, enhance soil microbial activity, and improve nutrient

cycling needed by rice crops. Over-application of lime to paddy fields could increase the pH over the optimum range and create a deficiency of soil micronutrients. Thus, the liming rates should always be based on laboratory assessments of soil samples.

Liming can be carried out at the start of the planting season while fields are prepared for planting. In the field, when conditions are relatively dry, lime must be uniformly spread over the surface of the soil, mixed with soil by ploughing or other farming implements, and left to react with the soil for

one or two weeks before planting.

3.4.2 Organic fertilizer application

Application of organic fertilizer is one of the important components in the plan to restore the soil fertility in the paddy fields in Konawe Regency, especially in the areas where there has been the degradation of soils due to the long and extensive applications of chemical fertilizers. Organic fertilizers add organic matter to the soil, which can improve the soil structure

and porosity, raise cation exchange capacity, and stimulate the activities of soil microbes [36]. All these elements have a great role in the recycling process of nutrients in rice agroecosystems. Besides, organic fertilizers help the efficient use of chemical fertilizers and the sustainability of rice production. Figure 5 demonstrates that high rates of compost organic fertilizer (COF) application are predominantly related to low levels of SOC, indicating that organic amendment is needed in places with organic matter deficiency.

Table 3. Alternative organic fertilizer recommendations for paddy agroecosystem in Konawe Regency

No.	Organic Fertilizer Type	Local Raw Materials	Form	Recommended Dose	Application Method
1	Cattle/Goat Manure	Local cattle and goat manure	Solid	10-20 tons ha ⁻¹	Evenly broadcast before planting
2	Rice Straw Compost	Rice straw from harvest residues	Solid	5-10 tons ha ⁻¹	Incorporated into the soil during land preparation
3	Leucaena green manure	Local leguminous plants	Fresh biomass	10-15 tons ha ⁻¹	Planted and incorporated into the soil before planting
4	Bio-Slurry	Solid residue from household biogas systems	Semi-liquid	5-10 tons ha ⁻¹	Mixed with soil before planting
5	Liquid Organic Fertilizer (LOF)	Kitchen waste, EM4, livestock urine	Liquid	250-500 mL per tank (16 L water)	Foliar spraying every 7-10 days
6	Market Waste Compost	Organic waste from traditional markets	Solid	5-10 tons ha ⁻¹	Mixed with soil during land preparation
7	Chicken Manure + Rice Husk Compost	Local poultry manure mixed with rice husk	Solid	5-10 tons ha ⁻¹	Broadcast 1 week before planting

Table 4. Generalized fertilizer adjustment strategy based on soil fertility status

Soil Condition	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Management Implication
Acidic soils with low SOC	Reduce or optimize	Maintain or slightly reduce	Increase	Improve nutrient use efficiency through liming and organic matter addition
Moderate fertility soils	Maintain	Maintain	Increase if K is low	Balance nutrient inputs with crop demand
Soils with nutrient imbalance (high N-P, low K)	Reduce	Reduce	Increase	Correct the imbalance to prevent yield limitation
Relatively fertile soils	Maintain	Maintain	Maintain	Sustain productivity with integrated management

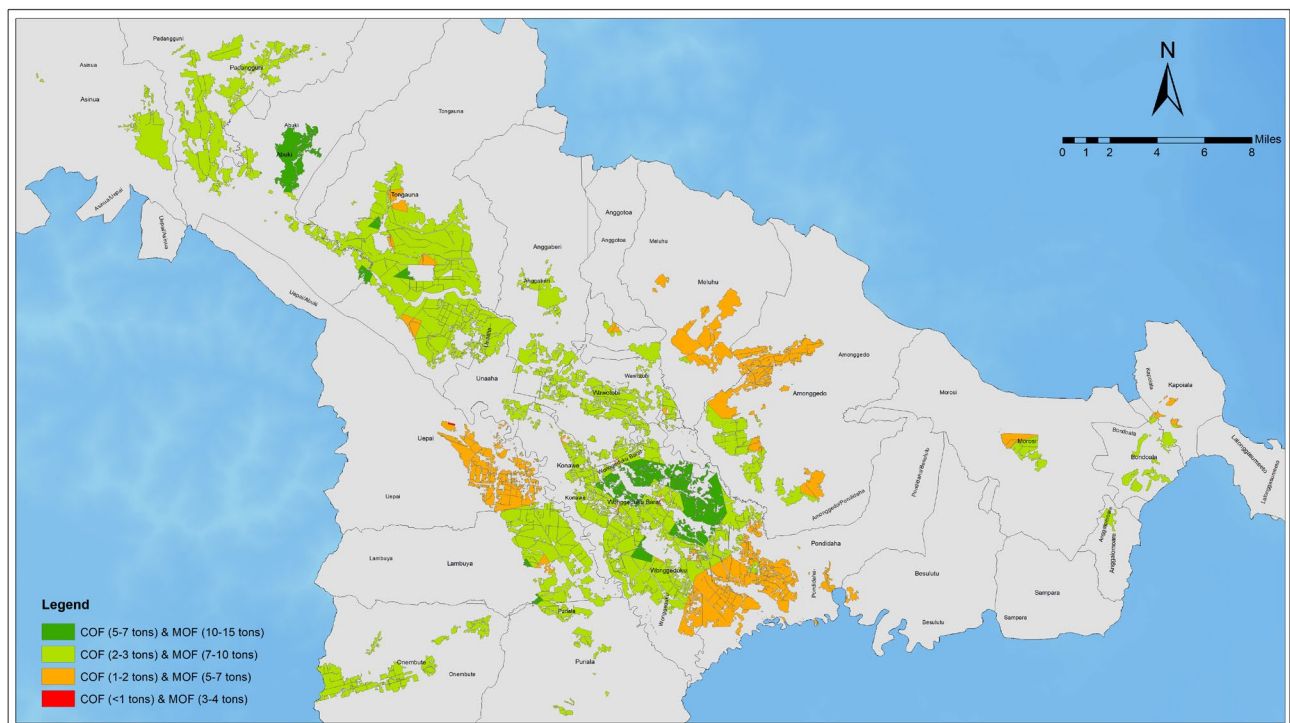


Figure 5. Spatial distribution of recommended compost organic fertilizer (COF) and microbial organic fertilizer (MOF) application rates for paddy agroecosystem in Konawe Regency, Southeast Sulawesi

Various organic fertilizers can be utilized on the basis of regional potentials and in consideration of the availability of local resources (Table 3). Organic fertilizers made from animal droppings can be used at a rate of 10-20 tons ha⁻¹ before planting to improve soil organic matter and macronutrients.

Application of organic fertilizer from rice straw compost should be 5-10 tons ha⁻¹ and mixed with soil during plowing to improve soil structure and recover nitrogen loss following harvesting. Local leguminous plants such as *Leucaena* (*Leucaena leucocephala*) and other legumes can be used as green manure at a rate of 10-15 tons ha⁻¹ before planting by planting them directly on the field before rice planting. The approach delivers nitrogen sources and degraded organic materials.

The application of bio-slurry, which comes from the by-product of domestic biogas production, can be applied at a rate of 5-10 tons ha⁻¹ and incorporated into the soil before planting to activate soil microorganisms and mineralize the nutrients faster. In addition to that, for micronutrient supply and nutrient efficiency uptake, LOF can be used by spraying every 7-10 days at a rate of 250-500 mL per tank (16 L of water), including kitchen wastes, livestock urine, and microbial activators. The distribution of LOF recommendations can be seen in Figure 5.

Furthermore, the compost obtained from organic waste from traditional markets or from chicken manure and rice husk can be used in the amount of 5 to 10 tons ha⁻¹ at the time of soil preparation or a week prior to plantation. The choice of organic fertilizer types and amounts should be tailored depending on the local availability of the raw materials used, farming systems adopted, and soil conditions. In order to guarantee a regular and sustainable source of organic fertilizer, there is a need to establish Organic Fertilizer Processing Units (OFPU) at the level of farmers' groups or villages.

These OFPUs will collect the raw materials, use microbial activators such as EM4 in the microbial decomposition of the raw materials to form fertilizer, and provide it to the farmers. Moreover, the combination of crop and livestock farming systems should be encouraged so that manure may regularly be available as a raw material for producing organic fertilizers.

3.4.3 Fertilization recommendations

Fertilization is an essential component to conduct fertilization in order to ensure proper nourishment of plants to fulfill their need for nutrients, hence, ensure good growth as well as enhance production levels [37]. The practice of fertilization has gained importance in the region of Konawe Regency since the soils in this particular location have suffered from degradation owing to excessive use of chemical fertilizers. Therefore, an effective fertilization plan should be developed based on the type of soil and the nutrients needed by crops (Table 4).

There are two ways of recommending the use of fertilizer, depending on the nature of the fertilizer. For instance, compound fertilizers contain more than one nutrient element, including types such as NPK 15-10-12, which can be found via subsidized programs provided by the government. Single fertilizers, on the other hand, contain only one nutrient element as urea (for nitrogen N), superphosphate fertilizer (SP-36) (for phosphorus P), and KCl (for potassium K). If single fertilizers are not available, the use of combined NPK fertilizers together with urea can be considered; conversely, if compound fertilizers are not accessible, then single fertilizers can be

recommended.

Fertilizer application management is an essential aspect in sustainable rice cultivation, especially in degraded paddy fields, where nutrient imbalance limits the efficiency of fertilizers used in farming activities. In line with the spatial variation of soil fertility characteristics, fertilizer suggestions have been made in an attempt to correlate the fertilizer needs with the soil conditions.

Instead of applying constant amounts of fertilizers, the present study makes suggestions on a function basis by taking into consideration soil pH, organic content, and fertility. The adjustments suggested in this study mainly relate to nitrogen and phosphorus, while there would be more potassium use in places where deficiency is identified.

These fertilizer suggestions are based on the nutrient status threshold levels obtained from the analysis of the 204 soil samples and have been made following the national standards for fertilization alongside other research findings in tropical paddy soils.

This shows that fertilization practices in the study region require a change from blanket application to more nutrient-oriented application based on site-specific conditions. Fertilizer inputs of nitrogen and phosphorus need to be decreased in some regions without any decrease in yield potential, as long as the limitations imposed by soil factors such as acidity and organic matter deficiency are taken into consideration. Potassium input should be increased in some regions due to its high tendency for leaching from soils in tropical conditions with low cation exchange capacity.

Fertilizer applications cannot stand alone but should be conducted together with efforts aimed at soil improvement. Liming soil leads to an increase in soil pH level, which will help in increasing phosphorus availability, whereas organic matter will increase nutrient retention in soil.

4. DISCUSSION

The analysis presented in Figure 6 shows that soil fertility decline in the rice agroecosystems in Konawe Regency is the result of several interacting chemical and biological factors. The presence of predominantly acidic soils, lower SOC, and imbalanced macronutrients, especially a deficiency in potassium, shows signs of a deterioration in the soil system's functional capability. Specifically, soil system theory implies that this will decrease the system's capacity to regulate nutrient turnover, maintain soil moisture, and support microbial activity, all key factors in the functioning of agroecosystems [38, 39].

One of the critical functions of the soil is the regulation of nutrient solubility and uptake. Low pH values in soil (soil pH < 5.5) increase the solubility of aluminium (Al³⁺) and iron (Fe²⁺) ions in soil. These compounds react with phosphate, thus making plant-available phosphorus unavailable, even though the total concentration of phosphate remains relatively high. Moreover, in the presence of low pH, leaching of base cations such as potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) takes place more rapidly, worsening macronutrient imbalance [34]. This is one explanation for higher than optimal levels of nutrients like nitrogen and phosphorus measured during the survey, but their inefficient utilization by crops. Soil pH is considered a primary variable in soil ecology since it regulates several soil processes [38].

The decrease in SOC content influences the physical

properties of soil and biological processes. The low level of SOC limits the capacity of the soil to hold nutrients like ammonium and potassium ions. SOC is a key regulator of redox dynamics and nutrient availability, especially nitrogen and phosphorus in flooded soils such as paddy fields. The low level of SOC suggests that there are carbon-limited systems. This means that the cycling of the nutrients within the soils will be limited and largely dependent on external sources [23, 40].

As can be observed from the statistics supplied, there is a big gap between the adequacy of nitrogen and phosphate and the deficit of potassium. This implies that fertilization does not correspond with the soil buffer and retention capacities. Potassium ions in worn soils, such as ultisols, are weakly attached to the soil due to the low CEC. This means that there will still be a potassium deficiency despite fertilizer application [41].

The suggested comprehensive management strategy integrates different techniques that can help solve the problems highlighted above. Liming helps reduce soil acidity by neutralizing the hydrogen ions and aluminum ions. Liming will also help increase the availability of phosphorus and stimulate root growth. Organic amendments will increase the CEC and improve soil aggregation.

From the viewpoint of ecological engineering, this methodology is seen as a transition from input-centered agricultural management to function-centered system design. While conventional methodologies involve merely increasing fertilizer inputs, the proposed strategy revolves around the restoration of processes related to nutrient cycling, transformation, and regulation. The main principle underlying ecological engineering is designing sustainable systems based on the integration of natural processes and human activity [42]. This key difference from conventional fertilizer management

cannot be overestimated: conventional fertilization treats the soil merely as an inert substrate and attempts to fill the yield gap through additional inputs, while the proposed methodology considers soil as an actively functioning biological system that requires initial restoration of its regulating capability before any input will become efficient. For example, liming is not only a pH correction but also a process restoration method, which allows increasing CEC, improving the microbial community performance, and reducing Al-P co-precipitation. In other words, this strategy enables more effective use of each following fertilizer application. Similarly, adding rice straw to the paddy field not only adds a carbon resource, but it also serves as a redox buffer when the paddy is flooded and provides a slowly available source of K and Si, which is usually not taken into account in traditional fertilizers' applications. In other words, the multifunctionality of soil amendment methods used in this study represents its theoretical value. Field evidence of the economic efficiency of the proposed methodology can also be found in similar tropical rice ecosystems. Namely, it was reported that liming at 1.5-2.0 tons per hectare, along with organic matter application at 5 tons per hectare increased rice grain yield by 0.5-0.9 tons per hectare in seasonal units, which translates into approximately IDR 1.5-2.7 million in net benefit at current prices for the region, whereas additional costs are about IDR 0.6-0.9 million per hectare [43]. In other words, the benefit-cost ratio is approximately 2:1 to 3:1, suggesting that the proposed restoration strategy is economically feasible under small-scale cultivation common in Konawe Regency. At the same time, adding rice straw improves not only soil fertility but also increases soil carbon content, soil structure, and reduces environmental problems related to burning rice residues [44].

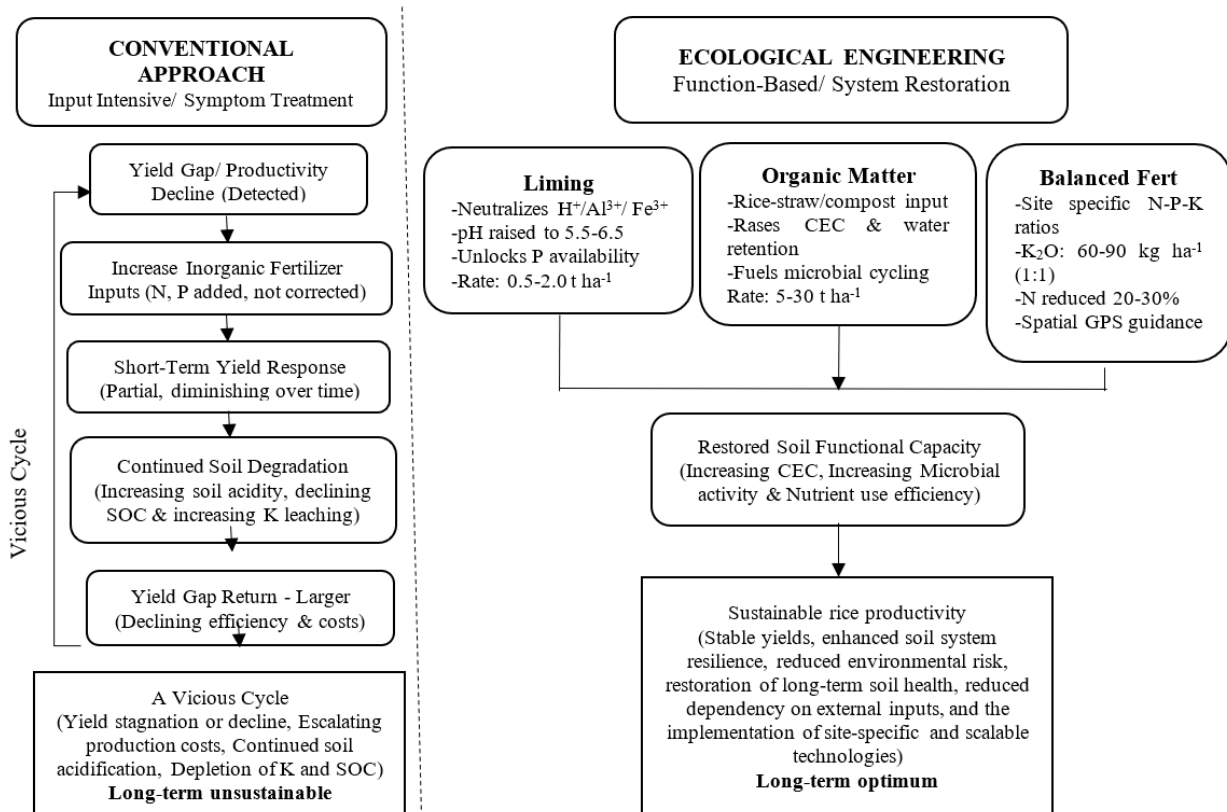


Figure 6. Conceptual framework comparing conventional input-intensive management with ecological engineering-based function-oriented soil restoration for paddy agroecosystems in Konawe Regency, Southeast Sulawesi

Overall, the research findings suggest that the improvement of rice yield in Konawe Regency needs the restoration of the soil functional integrity, not merely an increase in the external inputs. Combining geographic soil assessment and function-based management provides an effective way to detect deterioration hotspots and perform site-specific interventions. This helps to improve the efficiency of nitrogen usage, and the resilience and long-term sustainability of paddy soils in tropical conditions.

5. CONCLUSIONS

The fertility of paddy field soils in the Konawe Regency region may be seen from numerous indicators to diminish, including the frequency of acidic soils, poor SOC content, and soil nutrient imbalances. Potassium is among the most limiting nutrients, especially due to its deficits in soils. Soil pH is a key regulating factor influencing nutrient availability and fertilizer efficiency; therefore, liming represents an important intervention for restoring soil function. A low amount of SOC limits recycling and soil capacity for absorption of nutrients. Hence, the management of organic matter is important, notably in situ use of rice straw. The results indicate that improving rice productivity cannot be achieved solely by increasing fertilizer inputs, but requires an integrated management approach that focuses on restoring soil function, which can be used as a basis for planning sustainable paddy agroecosystems development in Konawe Regency.

REFERENCES

- [1] Rahman, A.R.B., Zhang, J. (2023). Trends in rice research: 2030 and beyond. *Food and Energy Security*, 12(2): e390. <https://doi.org/10.1002/fes3.390>
- [2] Sugiman, S.B., Fadwiwati, A.Y., Bungati, Raharjo, D. (2023). Farmers response to introducing of integrated crop management technology for lowland rice in Konawe District. In *IOP Conference Series: Earth and Environmental Science*, 1230(1): 012208. <https://doi.org/10.1088/1755-1315/1230/1/012208>
- [3] Rianti, A.T., Bafadal, A., Abdi, A. (2023). The forecasting analysis of rice production and sufficiency consumption of rice (*Oryza sativa*) in Konawe District. *Jurnal Ilmiah Membangun Desa dan Pertanian*, 8(3): 88-93. <https://doi.org/10.37149/jimdp.v8i3.131>
- [4] BPS-Statistics Indonesia Konawe Regency. (2024). Konawe Regency in Figures 2023, Unaaha, Southeast Sulawesi, Indonesia.
- [5] Qiao, L., Wang, X., Smith, P., Fan, J., et al. (2022). Soil quality both increases crop production and improves resilience to climate change. *Nature Climate Change*, 12(6): 574-580. <https://doi.org/10.1038/s41558-022-01376-8>
- [6] Wang, S., Xiao, L., Smith, P., Luo, Z., Zhuang, J., Yu, L., Zhu, Y. (2026). Improving soil quality enables reductions in nitrogen application rate in China's rice production systems. *Agricultural Systems*, 231: 104544. <https://doi.org/10.1016/j.agsy.2025.104544>
- [7] Zhang, X., Xiang, D.Q., Yang, C., Wu, W., Liu, H.B. (2022). The spatial variability of temporal changes in soil pH affected by topography and fertilization. *Catena*, 218: 106586. <https://doi.org/10.1016/j.catena.2022.106586>
- [8] Barrow, N.J., Hartemink, A.E. (2023). The effects of pH on nutrient availability depend on both soils and plants. *Plant and Soil*, 487(1): 21-37. <https://doi.org/10.1007/s11104-023-05960-5>
- [9] Bashir, O., Ali, T., Baba, Z.A., Rather, G.H., et al. (2021). Soil organic matter and its impact on soil properties and nutrient status. *Microbiota and Biofertilizers*, 129-159. https://doi.org/10.1007/978-3-030-61010-4_7
- [10] Zhang, C., Zhao, Z., Li, F., Zhang, J. (2022). Effects of organic and inorganic fertilization on soil organic carbon and enzymatic activities. *Agronomy*, 12(12): 3125. <https://doi.org/10.3390/agronomy12123125>
- [11] Ma, G., Cheng, S., He, W., Dong, Y., Qi, S., Tu, N., Tao, W. (2023). Effects of organic and inorganic fertilizers on soil nutrient conditions in rice fields with varying soil fertility. *Land*, 12(5): 1026. <https://doi.org/10.3390/land12051026>
- [12] Abate, E., Hussein, S., Laing, M., Mengistu, F. (2021). Soil acidity management in sub-Saharan Africa: A review of challenges and opportunities. *Soil and Tillage Research*, 209: 104940. <https://doi.org/10.1016/j.still.2021.104940>
- [13] Aumtong, S., Chotamonsak, C., Glomchinda, T. (2023). Study of the interaction of dissolved organic carbon, available nutrients, and clay content driving soil carbon storage in the rice rotation cropping system in northern Thailand. *Agronomy*, 13(1): 142. <https://doi.org/10.3390/agronomy13010142>
- [14] Qiu, L., Xu, X., Liu, J., Liu, K., Lu, S., Ge, T., Zhu, Z., Li, L., Xu, M., Chen, J., Yuan, Z., Zhang, Y. (2026). Paddy soil acidification: causes, harms, and mitigation measures. *Environmental Reviews*, 34: 1-15. <https://doi.org/10.1139/er-2025-0188>
- [15] Dessureault-Rompré, J. (2022). Restoring soil functions and agroecosystem services through phytotechnologies. *Frontiers in Soil Science*, 2: 927148. <https://doi.org/10.3389/fsoil.2022.927148>
- [16] Tarfa, A., Badiru, A.B. (2025). Systems engineering framework for environmental conservation and restoration management. In *Handbook of Emergency Response*, CRC Press, pp. 417-455.
- [17] Crusciol, C.A.C., Momesso, L., de Campos, M., Bossolani, J.W., Portugal, J.R., Moretti, L.G., Volf, M.R., Calonego, J.C., Rosolem, C.A. (2021). Liming optimizes nitrogen fertilization in a maize-upland rice rotation under no-till conditions. *Agronomy*, 11(10): 2005. <https://doi.org/10.3390/agronomy11102005>
- [18] Ando, K., Yamaguchi, N., Kasuya, M., Oga, T., Ohashi, Y., Taki, K. (2022). Long-term (nearly a century) effects of fertilizer, lime and rice straw compost application on active aluminum and iron and available phosphorus in paddy fields. *Geoderma*, 424: 115992. <https://doi.org/10.1016/j.geoderma.2022.115992>
- [19] Fernández-Ugalde, O., Jones, A., Meuli, R.G. (2020). Comparison of sampling with a spade and gouge auger for topsoil monitoring at the continental scale. *European Journal of Soil Science*, 71(2): 137-150. <https://doi.org/10.1111/ejss.12862>
- [20] Agricultural Instrument Standardization Agency. (2023). *Technical Guidelines for Chemical Analysis of Soil, Aquatic Plants, and Fertilizers (3rd Edition, 2023)*. Agricultural Land Resources Instrument Standards Testing Center, Ministry of Agriculture, Republic of Indonesia.

- [21] Panigrahi, N. (2023). Inverse distance weight. In Encyclopedia of Mathematical Geosciences, Encyclopedia of Earth Sciences Series, pp. 666-672. https://doi.org/10.1007/978-3-030-85040-1_166
- [22] Mosley, L.M., Rengasamy, P., Fitzpatrick, R. (2024). Soil pH: Techniques, challenges and insights from a global dataset. *European Journal of Soil Science*, 75(6): e70021. <https://doi.org/10.1111/ejss.70021>
- [23] Zhang, Z., Xie, D., Teng, W., Gu, F., Zhang, R., Cheng, K., Liu, Zhuqing, L., Ying, Z., Yang, F. (2025). A state of art review on carbon, nitrogen, and phosphorus cycling and efficient utilization in paddy fields. *Plant and Soil*, 513(2): 1689-1709. <https://doi.org/10.1007/s11104-025-07344-3>
- [24] Jamaludin, A.F., Jusop, S., Panhwar, Q.A., Anuar, M.F.M., Naher, U.A. (2026). Alleviating soil acidity, Al³⁺ and/or Fe²⁺ toxicity for sustainable rice production on acid sulfate soils. *Pakistan Journal of Botany*, 58(2): 369-378. [http://doi.org/10.30848/PJB2026-2\(8\)](http://doi.org/10.30848/PJB2026-2(8))
- [25] Prakash, J., Agrawal, S.B., Agrawal, M. (2023). Global trends of acidity in rainfall and its impact on plants and soil. *Journal of Soil Science and Plant Nutrition*, 23(1): 398-419. <https://doi.org/10.1007/s42729-022-01051-z>
- [26] Suntoro, S., Herdiansyah, G., Widijanto, H., Minardi, S., Dewi, F.S. (2024). Evaluation of soil fertility index in organic, semi-organic, and conventional rice field management systems. *Scientia Agropecuaria*, 15(2): 163-175. <https://doi.org/10.17268/sci.agropecu.2024.012>
- [27] Page, K.L., Dang, Y.P., Dalal, R.C. (2020). The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. *Frontiers in Sustainable Food Systems*, 4: 31. <https://doi.org/10.3389/fsufs.2020.00031>
- [28] Purwanto, B.H., Alam, S. (2020). Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. *Soil Science and Plant Nutrition*, 66(1): 50-59. <https://doi.org/10.1080/00380768.2019.1705182>
- [29] Qaswar, M., Huang, J., Ahmed, W., Li, D., Liu, S., Lu, Z., Cai, A., Liu, L., Xu, Y., Gao, J., Zhang, H. (2020). Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. *Soil and Tillage Research*, 198: 104569. <https://doi.org/10.1016/j.still.2019.104569>
- [30] Yang, Q., Zheng, F., Jia, X., Liu, P., Dong, S., Zhang, J., Zhao, B. (2020). The combined application of organic and inorganic fertilizers increases soil organic matter and improves soil microenvironment in wheat-maize field. *Journal of Soils and Sediments*, 20(5): 2395-2404. <https://doi.org/10.1007/s11368-020-02606-2>
- [31] Sinha, D., Tandon, P.K. (2020). An overview of nitrogen, phosphorus and potassium: Key players of nutrition process in plants. In: Mishra, K., Tandon, P.K., Srivastava, S. (eds) *Sustainable Solutions for Elemental Deficiency and Excess in Crop Plants*, Springer, pp. 85-117. https://doi.org/10.1007/978-981-15-8636-1_5
- [32] Viancelli, A., Michelon, W. (2024). Climate change and nitrogen dynamics: Challenges and strategies for a sustainable future. *Nitrogen*, 5(3): 688-701. <https://doi.org/10.3390/nitrogen5030045>
- [33] Sulaeman, Y., Maftuáh, E., Noor, M., Hairani, A., Nurzakiah, S., Mukhlis, M., Anwar, K., Fahmi, A., Saleh, M., Khairullah, I., Rumanti, I.A., Alwi, M., Noor, A., Ningsih, R.D. (2024). Coastal acid-sulfate soils of Kalimantan, Indonesia, for food security: Characteristics, management, and future directions. *Resources*, 13(3): 36. <https://doi.org/10.3390/resources13030036>
- [34] Warke, A., Wakgari, T. (2024). A review on the impact of soil acidification on plant nutrient availability, crop productivity, and management options. *Forestry and Fisheries*, 13(2): 31-45. <https://doi.org/10.11648/j.aff.20241302.13>
- [35] Junior, E.C., Gonçalves Jr, A.C., Seidel, E.P., Ziemer, G.L., Zimmermann, J., de Oliveira, V.H.D., Schwantes, D., Zeni, C.D. (2020). Effects of liming on soil physical attributes: A review. *Journal of Agricultural Science*, 12(10): 278. <https://doi.org/10.5539/jas.v12n10p278>
- [36] Bolan, N., Srivastava, P., Rao, C.S., Satyanaraya, P.V., et al. (2023). Distribution, characteristics and management of calcareous soils. *Advances in Agronomy*, 182: 81-119. <https://doi.org/10.1016/bs.agron.2023.06.002>
- [37] Aytenew, M., Bore, G. (2020). Effects of organic amendments on soil fertility and environmental quality: A review. *Journal of Plant Sciences*, 8(5): 112-119. <https://doi.org/10.11648/j.jps.20200805.12>
- [38] Shrestha, J., Karki, T.B., Hossain, M.A. (2022). Application of nitrogenous fertilizer in rice production: A review. *Journal of Nepal Agricultural Research Council*, 8: 16-26. <https://doi.org/10.3126/jnarc.v8i.44815>
- [39] Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B.C., Munda, S., Dari, B. (2022). A review on effective soil health bio-indicators for ecosystem restoration and sustainability. *Frontiers in Microbiology*, 13: 938481. <https://doi.org/10.3389/fmicb.2022.938481>
- [40] Sharma, S., Lishika, B., Kaushal, S. (2023). Soil quality indicators: A comprehensive review. *International Journal of Plant & Soil Science*, 35(22): 315-325. <https://doi.org/10.9734/ijpss/2023/v35i224139>
- [41] Abdallah, A.M., Jat, H.S., Choudhary, M., Abdelaty, E.F., Sharma, P.C., Jat, M.L. (2021). Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A review. *Agronomy*, 11(9): 1681. <https://doi.org/10.3390/agronomy11091681>
- [42] Mitsch, W.J., Jørgensen, S.E. (2004). *Ecological Engineering and Ecosystem Restoration*. Hoboken, N.J: Wiley.
- [43] Naorem, A., Jayaraman, S., Dang, Y.P., Dalal, R.C., Sinha, N.K., Rao, C.S., Patra, A.K. (2023). Soil constraints in an arid environment-challenges, prospects, and implications. *Agronomy*, 13(1): 220. <https://doi.org/10.3390/agronomy13010220>
- [44] Battaglia, M., Thomason, W., Fike, J.H., Evanylo, G.K., von Cossel, M., Babur, E., Iqbal, Y., Diatta, A.A. (2021). The broad impacts of corn stover and wheat straw removal for biofuel production on crop productivity, soil health and greenhouse gas emissions: A review. *Gcb Bioenergy*, 13(1): 45-57. <https://doi.org/10.1111/gcbb.12774>