JUATIKA
JURNAL AGRONOMI TANAMAN TROPIKA
VOL. 8 No. 3 September 2026

DOI :https://doi.org/10.36378/juatika.v8i3.5891
eissn 2656-1727
pissn 2684-785X
pages : 999 – 1008

RESEARCH ARTICLE Open Access

Soil Organic Carbon Degradation and Changes In Phosphorus and Potassium Status in Intensive Paddy Fields of Solok Regency and Solok City, West Sumatra, Indonesia

Ismon Lenin[1,2], Hermansah[1*], Agustian[1], Auzar Syarif[1], Ai Dariah[2]

Abstract

Rice yield stagnation in intensive paddy fields has been widely associated with declining soil organic carbon (SOC) and nutrient imbalance. This study aimed to quantify the extent and spatial distribution of SOC, phosphorus (P), and potassium (K) status in paddy fields in Solok Regency and Solok City, West Sumatra, Indonesia, and to evaluate opportunities to improve soil fertility to support sustainable rice production. The study covered 23,426 ha of paddy fields, consisting of 22,551 ha in Solok Regency and 876 ha in Solok City. Soil fertility status was assessed based on SOC, available P, and exchangeable K. Results showed that 68.24% of the paddy fields had low SOC content (<2%), indicating widespread soil organic matter depletion. In contrast, 85.47% and 72.91% of the area exhibited high P and K status, respectively, reflecting substantial nutrient accumulation from long-term fertilization. These findings indicate that soil fertility management should prioritize increasing soil organic carbon (SOC) and optimizing the use of accumulated phosphorus (P) and potassium (K) reserves (*legacy nutrients*) to improve fertilizer use efficiency. To enhance the productivity of lowland rice soils in Solok Regency and Solok City, organic amendments should be applied, together with P and K fertilization tailored to the soil nutrient status. This approach could improve soil health, sustain rice productivity, and support the long-term sustainability of intensive lowland rice farming systems.

Keywords: Legacy Nutrients, Lowland Rice, Nutrient Imbalance, Organic Matter, Soil Organic Carbon

1. Introduction

Rice (*Oryza sativa* L.) is one of the major staple food crops that plays a critical role in ensuring global food and nutritional security, particularly in South and Southeast Asia (Ladha et al., 2022). However, rice productivity in many countries, including Indonesia, has exhibited signs of yield stagnation (leveling off) over the past two decades (Maulana, 2004; Sulaeman et al., 2024). This phenomenon is also evident in Solok Regency, West Sumatra. Rice productivity in this region declined from 5.68 t ha^{-1} in 2017 to 4.64 t ha^{-1} in 2020, and although it increased again to 5.60 t ha^{-1} in 2025, it remains lower than the 2017 level (BPS, 2023; Distan, 2026). These trends indicate a long-term tendency toward rice yield stagnation in the region.

Rice yield stagnation is closely associated with the increasing extent of marginal and degraded paddy fields, environmental stress, and suboptimal nutrient management practices (Lenin et al., 2021; Lenin and Siska, 2018a; Sembiring et al., 2020). Paddy field degradation is primarily characterized by a decline in soil organic carbon content, nutrient imbalance due to the accumulation of phosphorus (P) and potassium (K), and reduced availability of silica (Husnain et al., 2016; Kasno, 2010; Schaller et al., 2022).

The decline in soil organic carbon is primarily attributed to intensive land management practices that are not balanced with the return of organic materials to the soil,

*Correspondence: hermansah@agr.unand.ac.id
1) Universitas Andalas – Jl. Dr. Mohammad Hatta, Kampus Limau Manis, Kecamatan Pauh, Kota Padang, Sumatera Barat 25163, Indonesia
2) Badan Riset dan Inovasi Nasional (BRIN) - Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Kabupaten Bogor, Jawa Barat 16911, Indonesia

as well as post-harvest rice straw burning practices (Agustina et al., 2020; Fachriansyah et al., 2023; Gummert et al., 2020; Saidy, 2018) In contrast, organic matter plays a crucial role in improving the physical, chemical, and biological properties of soils, as well as enhancing the soil's capacity to supply nutrients to plants (Voltr et al., 2021; Zhang et al., 2025). The decline in soil organic carbon (SOC) not only reduces the carbon supply for soil biological activity but may also impair the soil's capacity to retain and recycle nutrients, thereby increasing the dependence of sustained rice productivity on external inputs (Supriyadi et al., 2022).

In addition, continuous fertilizer application without considering soil nutrient status can lead to phosphorus (P) and potassium (K) accumulation, nutrient imbalance, and reduced fertilizer-use efficiency(Fang et al., 2026; Husnain et al., 2016). Excessive accumulation of phosphorus can decrease the availability of micronutrients, particularly Fe, Zn, and Cu, thereby inhibiting plant growth even when soil P levels are high (Babu et al., 2016; Bhat et al., 2024; Hermansah et al., 2009). These conditions result in reduced crop responsiveness to fertilization and lower nutrient-use efficiency (Lenin, 2016; Lenin and Siska, 2018a; Yu et al., 2026). Therefore, in soils with moderate to high P status, P fertilizer application should be reduced by 50–70% of the standard recommended dose (Husnain et al., 2016).

Nutrient accumulation problems have been widely reported in rice production centers in West Sumatra. In Padang City, approximately 92.7% of the total 8,805 ha of paddy fields exhibit high phosphorus (P) status. Meanwhile, in Agam Regency, about 75.3% of paddy fields are classified as having high P status and 66% as having high potassium (K) status (Burbey et al., 2005). These findings indicate that soil organic carbon degradation and nutrient imbalance are critical issues that require serious attention in paddy field management.

Effective soil fertility management requires accurate spatial information on the degree of soil organic carbon degradation and on phosphorus (P) and potassium (K) status. Therefore, mapping the distribution and extent of paddy fields experiencing soil organic carbon decline and changes in P and K status is necessary in Solok Regency and Solok City. Such information can be used to set land management priorities, develop site-specific fertilizer recommendations, improve fertilizer-use efficiency, and support sustainable increases in rice productivity. In addition, the mapping results can serve as a basis for determining district-level fertilizer requirements, enabling more precise and efficient fertilizer planning and distribution (Sukarman et al., 2012; Wahyunto and Dariah, 2014).

However, previous studies in West Sumatra have largely focused on individual soil fertility constraints or specific locations, providing limited information on the spatial integration of soil organic carbon (SOC) degradation with phosphorus (P) and potassium (K) status across intensively cultivated lowland rice areas. Consequently, the extent and spatial distribution of SOC depletion occurring concurrently with P and K accumulation remain poorly characterized, particularly in Solok Regency and Solok City, which are important rice-producing areas of West Sumatra.

This knowledge gap limits the development of spatially targeted soil fertility management strategies because areas with depleted SOC may require organic amendments, whereas soils with accumulated P and K may require reduced or adjusted fertilizer inputs. Therefore, this study aimed to quantify and spatially characterize the distribution and extent of lowland rice soils with different SOC, P, and K status classes across Solok Regency and Solok City, West Sumatra.

The novelty of this study lies in integrating the spatial assessment of SOC, P, and K status to identify the dominant soil fertility imbalance across an intensively cultivated rice-growing region. By quantifying the area affected by SOC depletion alongside P and K accumulation, this study provides a spatially explicit basis for prioritizing organic matter management, adjusting P and K fertilization according to soil nutrient status, and improving fertilizer-use efficiency. The resulting soil fertility map can also serve as a baseline for site-specific nutrient management and regional fertilizer planning to support the long-term sustainability of intensive lowland rice production.

2. Material and Methods

The study was conducted in irrigated lowland rice fields in Solok Regency and Solok City, West Sumatra Province, Indonesia. Soil sampling sites were located at elevations ranging from 304 to 1,254 m above sea level, with geographic coordinates ranging from 00°57′19.4″ to 01°04′54.8″ S and from 100°36′40.3″ to 100°52′43.8″ E. The spatial distribution of the soil sampling points is presented in the operational map (Fig. 1).

Soil analyses were carried out at the Soil and Plant Laboratory of the Assessment Institute for Agricultural Technology (AIAT) of West Sumatra.

The materials and instruments used in this study included topsoil samples (0–20 cm), administrative boundary maps, land-use maps, the Indonesian Topographic Map (Rupa Bumi Indonesia) at 1:50,000 scale from the Geospatial Information Agency (BIG, 2013), the Ministry of Agriculture rice field map (2013), Google Earth imagery (2016), soil type maps, Sentinel-2 or Landsat 8 satellite imagery, Digital Elevation Model (DEM) data, a handheld GPS device, a soil auger, and sample bags.

The study was conducted through several stages: (1) preparation of an operational map. A 1:25,000-scale operational map was used as a guide for field surveys. This map was developed based on the Indonesian Topographic

Map (Rupa Bumi Indonesia) at a 1:50,000 scale (BIG, 2013), the Ministry of Agriculture rice field map (2013), and Google Earth imagery (2016). Based on this operational map, a soil sampling design was established using a grid system with a spacing of 2 cm on the map or approximately 500 m in the field, (2) Survey and mapping of soil organic carbon (SOC), phosphorus (P), and potassium (K) status were conducted through several steps: (a) pre-survey activities, which included consultations and discussions on fertilizer management practices at the farmer level with the District Agricultural Offices and Agricultural Extension Centers across Solok Regency and Solok City, as well as discussions with the National Land Agency (BPN) regarding the acquisition of administrative boundary maps and land-use maps; (b) the main survey, which involved soil sampling. Soil samples were subsequently analyzed at the Soil and Plant Laboratory of the West Sumatra Assessment Institute for Agricultural Technology (WS-AIAT), Sukarami, Solok, West Sumatra, Indonesia

Composite soil sampling was conducted at predetermined locations defined on the operational map (Figure 1). Each composite sample consisted of 10–15 individual subsamples, collected at intervals of 20–50 m in the field. Soil samples were collected from the plow layer at 0–20 cm depth, and geographic coordinates were recorded with a Garmin 78s device. One composite sample represented an area of approximately 25 ha. Individual subsamples were placed in a bucket and thoroughly mixed until homogeneous, after which approximately 0.5–1 kg of the composite sample was taken for analysis (Wahyunto et al., 2016).

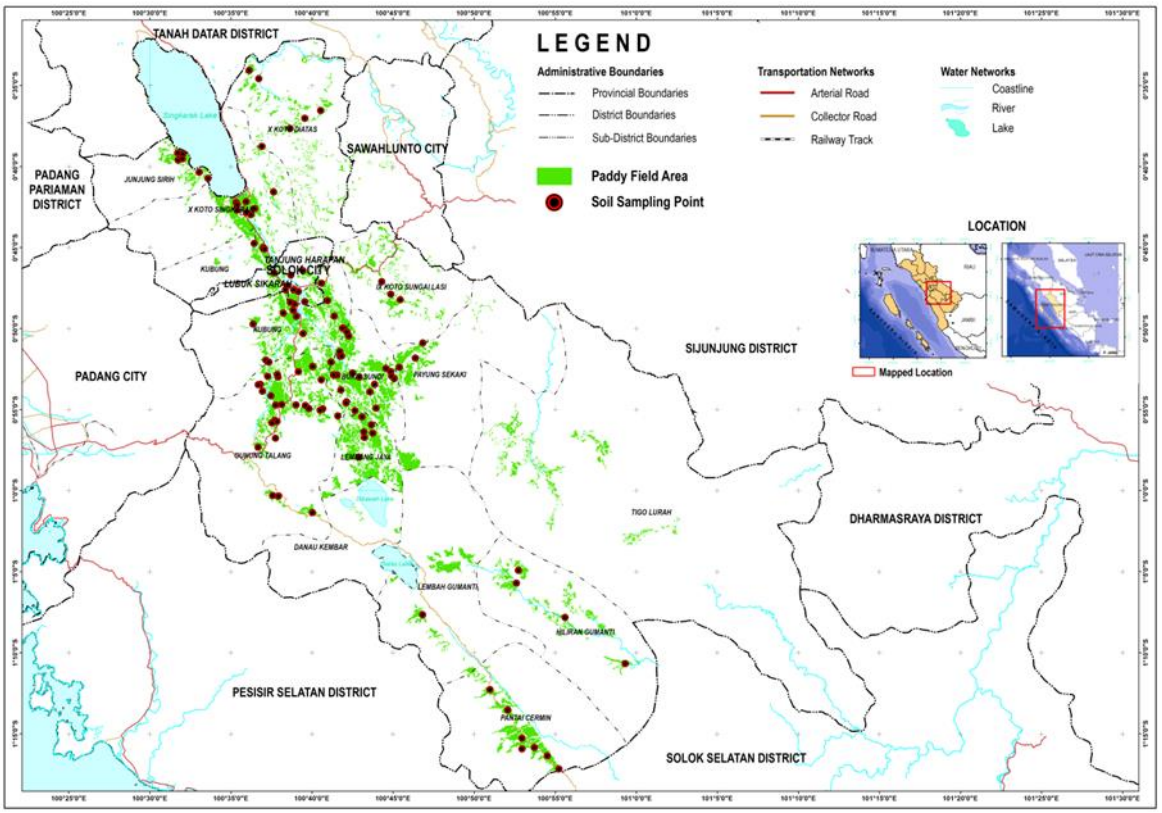


Figure 1. Operational map and soil sampling locations in paddy fields of Solok Regency and Solok City, West Sumatra, Indonesia.

A total of 121 composite soil samples were collected and analyzed in the laboratory. Soil available phosphorus (P) and potassium (K) were determined using a 25% HCl extraction procedure, whereas soil organic carbon (SOC) was measured following the Walkley–Black wet oxidation method using $K_2 Cr_2 O_7$ (potassium dichromate) as the oxidizing agent. The analytical data were georeferenced and interpolated onto a base map according to the coordinates of each sampling point. The resulting thematic maps were classified into three status categories, namely low, moderate, and high, which were represented by red, yellow, and green colors, respectively.

Soil fertility status was evaluated based on soil organic carbon (SOC), phosphorus (P), and potassium (K) concentrations. SOC status was classified as low (<2%), moderate (2–4%), or high (>4%). Phosphorus status was categorized as low (< 20 mg $P_2 O_5$ 100 g^{-1} soil), moderate (20–40 mg $P_2 O_5$ 100 g^{-1} soil), and high (> 40

mg P_2 O_5 100 g^{-1} soil). Potassium status was similarly classified as low (< 10 mg K_2 O 100 g^{-1} soil), moderate (10–20 mg K_2 O 100 g^{-1} soil), and high (> 20 mg K_2 O 100 g^{-1} soil) according to the soil fertility evaluation criteria established by Syofyan et al. (2000; 2004).

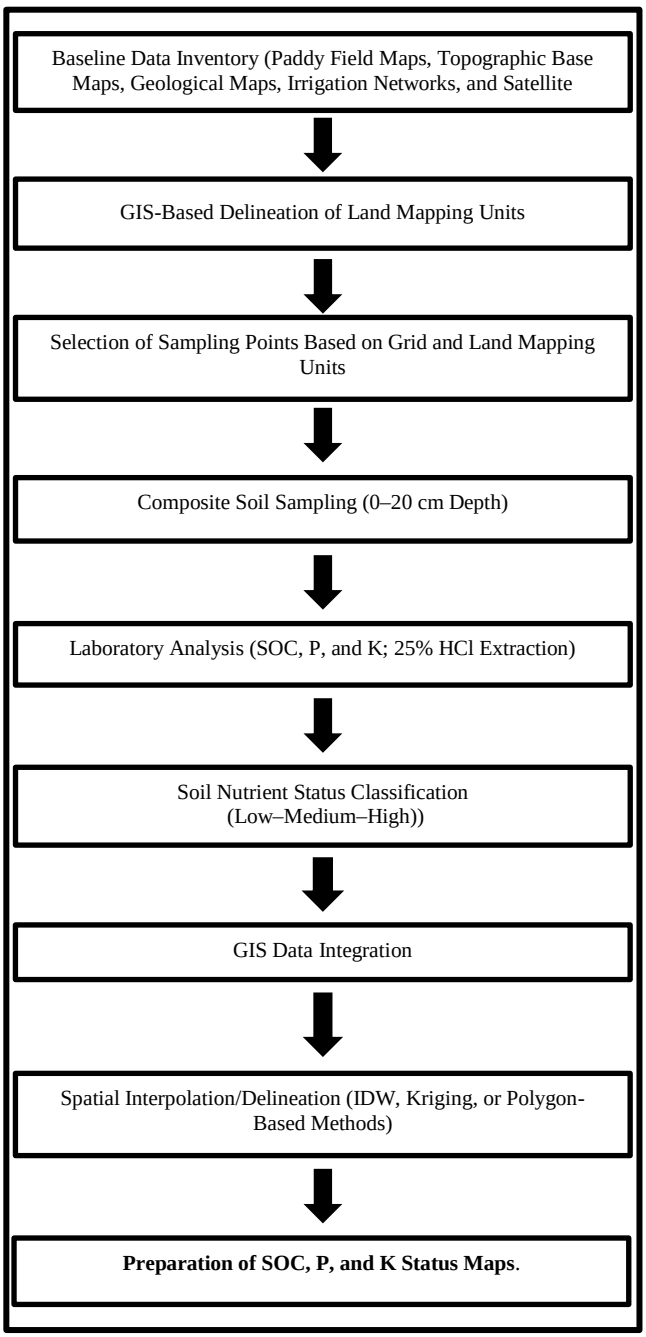


Figure 2. Research workflow for the spatial mapping of soil organic carbon (SOC), phosphorus (P), and potassium (K) status in paddy fields across Solok Regency and Solok City.

The delineation of soil organic carbon (SOC), phosphorus (P), and potassium (K) status maps was performed by integrating soil analytical data with several environmental factors, including parent material, soil type, topography/landform characteristics, and natural boundaries such as rivers and roads. Each mapping unit was assigned a color corresponding to its fertility status class based on the established classification criteria. Final map production was completed in ArcGIS 10.6. As a result, three thematic maps were generated: (1) a soil organic carbon (SOC) status map of paddy fields, (2) a soil phosphorus (P) status map of paddy fields, and (3) a soil potassium (K) status map of paddy fields. The workflow employed for mapping SOC, P, and K status in paddy fields across Solok Regency and Solok City is presented in Figure 2.

3. Results and Discussion

3.1. Soil Organic Carbon Status in Paddy Fields of Solok Regency and Solok City

The total paddy field area in Solok Regency and Solok City covers 23,426 ha, comprising 22,551 ha within the administrative boundary of Solok Regency and 876 ha within Solok City. The results of the 1:50,000-scale soil organic carbon (SOC) status mapping revealed that 15,985 ha (68.24%) of the paddy fields were classified as having low SOC content, distributed across nearly all districts. Areas with moderate SOC content covered 7,285 ha (31.10%), while only 156 ha (0.67%) were classified as having high SOC content. The spatial distribution of SOC status in the paddy fields of Solok Regency and Solok City at a scale of 1:50,000 is presented in Figure 3.

The extensive area of paddy fields characterized by low soil organic carbon (SOC) content is likely associated with the long-term intensification of rice cultivation systems. The increase in cropping intensity from 2 to 2.5–3.0 cropping cycles per year has encouraged farmers to accelerate land preparation to meet planting-season schedules. Consequently, post-harvest rice straw burning has become a common practice (Figure 4), preventing the return of substantial amounts of biomass to the soil. As a result, a valuable source of organic carbon is lost, thereby limiting the replenishment and accumulation of SOC in paddy ecosystems.

Rice straw burning causes a substantial proportion of biomass-derived carbon to be oxidized and released into the atmosphere as CO_2 and other carbon-containing compounds (Sanchis Jiménez et al., 2014) In addition to increasing greenhouse gas and particulate matter emissions, this practice removes a significant potential source of carbon input to the soil (Chen et al., 2026; Sullivan et al., 2026; Zhou et al., 2014).

Intensive tillage practices further contribute to soil organic carbon (SOC) degradation in paddy fields. Plowing and harrowing disrupt soil aggregates, exposing previously protected organic matter and increasing its contact with microorganisms and oxygen. These processes accelerate

organic matter mineralization, resulting in greater carbon losses through CO_2 emissions and a more rapid decline in SOC stocks (Hussain et al., 2021; Koushika et al., 2024; Naorem et al., 2023).

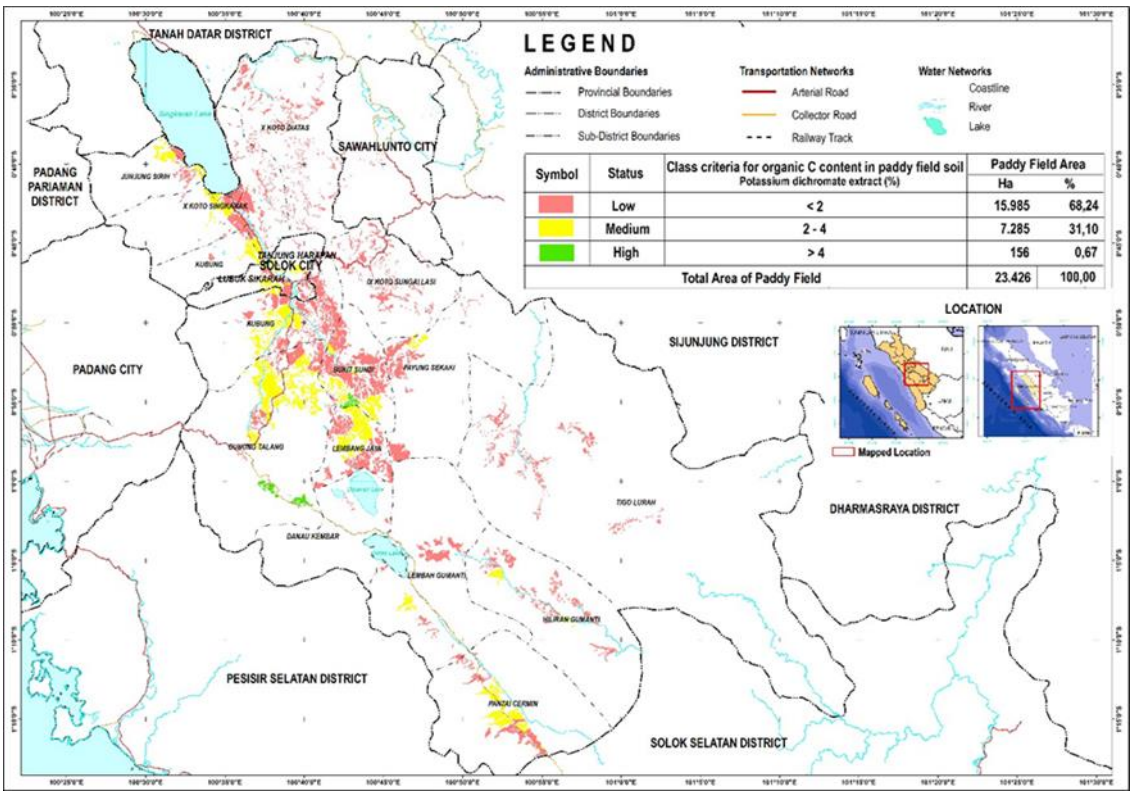


Figure 3. C-organic status map of rice fields in Solok district and city, scale 1:50,000

In paddy systems, reduced tillage intensity has been reported to increase soil organic carbon (SOC) storage by up to 5.85 Mg C ha^{-1} and decrease CO_2 fluxes by 14.5% compared with plow tillage after 11 years of implementation. In addition, no-tillage practices can increase SOC by 7–48% in the 0–5 cm soil layer relative to conventional tillage. These findings indicate that reducing soil disturbance may help conserve SOC by enhancing aggregate stability and the physical protection of organic matter (Wang et al., 2020).

In addition to the widespread practice of burning rice straw, the application of external organic amendments, such as farmyard manure and compost, remains generally limited. This condition results in insufficient carbon inputs to the soil, while carbon losses through decomposition and mineralization continue unabated. According to (Naorem et al., 2023), such an imbalance between carbon inputs and outputs leads to a negative soil carbon balance, ultimately reducing soil organic matter reserves and accelerating the degradation of paddy soil quality.

A decline in soil organic carbon (SOC) content reduces soil aggregate stability, cation exchange capacity (CEC), and microbial activity, ultimately leading to nutrient imbalances and lower fertilizer use efficiency. These adverse changes contribute to the occurrence of yield stagnation (leveling-off) in paddy fields, thereby constraining further increases in rice productivity (Supriyadi et al., 2020).

The application of organic amendments, including farmyard manure, rice straw compost, and other organic materials, can enhance soil carbon accumulation, improve soil structure, and strengthen the soil's capacity to maintain its ecological functions. Increased soil organic matter content also positively affects crop productivity and nutrient use efficiency. Expanding the use of organic fertilizers represents a strategic approach to mitigating the degradation of soil organic carbon (SOC) in paddy fields. Therefore, the adoption of organic fertilization practices should be continuously promoted as an integral component of sustainable soil fertility management (Wihardjaka and Harsanti, 2020).

Paddy fields with high soil organic carbon (SOC) status (>4%) in Solok Regency and Solok City cover only approximately 156 ha, representing 0.67% of the total paddy field area. These areas are primarily concentrated in the highland regions surrounding Mount Talang, where soils are predominantly classified as Andisols. The elevated SOC content observed in these paddy fields is consistent with the typical characteristics of Andisols in Indonesia, which generally contain high (>3%) to very high (>5%) levels of organic carbon (Yatno and Suharta, 2011).

The capacity of Andisols to accumulate and retain soil organic carbon is closely associated with the presence of aluminum–humus (Al–humus) complexes, which serve as a

primary mechanism for stabilizing soil organic matter. The formation of Al–humus complexes protects organic matter from microbial decomposition, thereby enhancing long-term carbon retention and storage. Consequently, carbon stocks in Andisols are generally substantially higher than those found in most other soil orders (Kusmiyarti and M Mega, N Dibia, 2005; Suryani et al., 2021).

.



Figure 4. Post-harvest rice straw burning, a major pathway of soil organic carbon loss in paddy fields of Solok Regency and Solok City

3.2. Phosphorus Nutrient Status in Paddy Fields of Solok Regency and Solok City

The results of phosphorus (P) nutrient status mapping in paddy fields based on the 1:50,000-scale soil nutrient status map indicate that 1,736 ha (7.41%) of the paddy fields are classified as low in P status, 1,668 ha (7.12%) as moderate, and 20,022 ha (85.47%) as high. The spatial distribution of soil P status in the paddy fields of Solok Regency and Solok City is presented in Figure 5. The predominance of high P status areas indicates extensive phosphorus accumulation (legacy phosphorus), which is likely a consequence of intensive cultivation practices and repeated applications of phosphate fertilizers at rates exceeding crop requirements over an extended period.

Intensive and long-term phosphorus (P) fertilization in paddy fields often exceeds crop requirements, leading to the accumulation of phosphorus, commonly referred to as legacy phosphorus in soils. This accumulation results from an imbalance between P inputs and outputs, whereby the amount of P applied through fertilizers and organic amendments exceeds that removed by plant uptake and harvested biomass. The excess P subsequently undergoes adsorption, precipitation, and immobilization processes, leading to its accumulation in various soil P fractions that are relatively less available to plants (Aumtong et al., 2023; Martinengo et al., 2023; Menezes-blackburn et al., 2018).

In lowland rice fields with a high soil P status based on 25% HCl-extractable P (>40 mg P_2O_5 100 g^{-1}) in Dharmasraya Regency, P fertilizer application did not increase rice yield, indicating that additional P may not be necessary in soils with already high P availability (Lenin, 2016). Moreover, P applied during the first growing season can be utilized by rice in the subsequent season through residual effects without reducing yield (Lenin and Siska, 2018b).

Global studies indicate that approximately 57% of soil phosphorus (P) stocks are stored in inorganic forms, while 33% occur as organic monoesters, with total legacy P reserves potentially exceeding 1,500 kg ha^{-1}. The organic P fraction is predominantly composed of phytate (myo-inositol hexakisphosphate), a relatively stable compound that serves as a long-term phosphorus reservoir. The magnitude of these reserves highlights their considerable potential for future nutrient recycling, although most of this phosphorus remains in forms that are poorly available to plants (Liu et al., 2022; Menezes-blackburn et al., 2018).

In paddy fields, phosphorus dynamics are more complex due to flooded conditions that create redox environments distinct from those in upland soils. Phosphorus availability and transformation are influenced not only by soil P content but also by the interactions among hydrological processes, biogeochemical reactions, and soil properties that govern phosphorus release and retention during alternating flooding and drainage periods (Palihakkara et al., 2024). These conditions contribute to changes in the forms and distribution of phosphorus accumulated in paddy soils.

Optimizing legacy phosphorus utilization requires management strategies that enhance phosphorus

mobilization and mineralization through chemical, biological, and fertilization approaches. The combined application of organic amendments and inorganic fertilizers has been shown to be more effective than sole chemical fertilization in improving soil organic carbon, soil pH, phosphorus availability, and plant phosphorus uptake (Hayatu et al., 2023). In addition, long-term fertilization practices influence the structure of phosphate-solubilizing microbial communities, which play a crucial role in phosphorus transformation and in supplying plant-available phosphorus (Chen et al., 2023).

The management of organic amendments not only improves the efficiency of soil phosphorus (P) reserve utilization but also contributes to soil organic carbon accumulation and the sustainability of paddy soil functions (Wang et al., 2023). Therefore, enhancing the efficiency of legacy phosphorus utilization through improved soil quality, optimization of organic inputs, and stimulation of phosphate-solubilizing microorganisms and phytase enzyme activity represents a key strategy to reduce dependence on external phosphate fertilizers, increase nutrient use efficiency, and support the sustainable productivity of rice systems (Ibrahim et al., 2022; Liu et al., 2022)

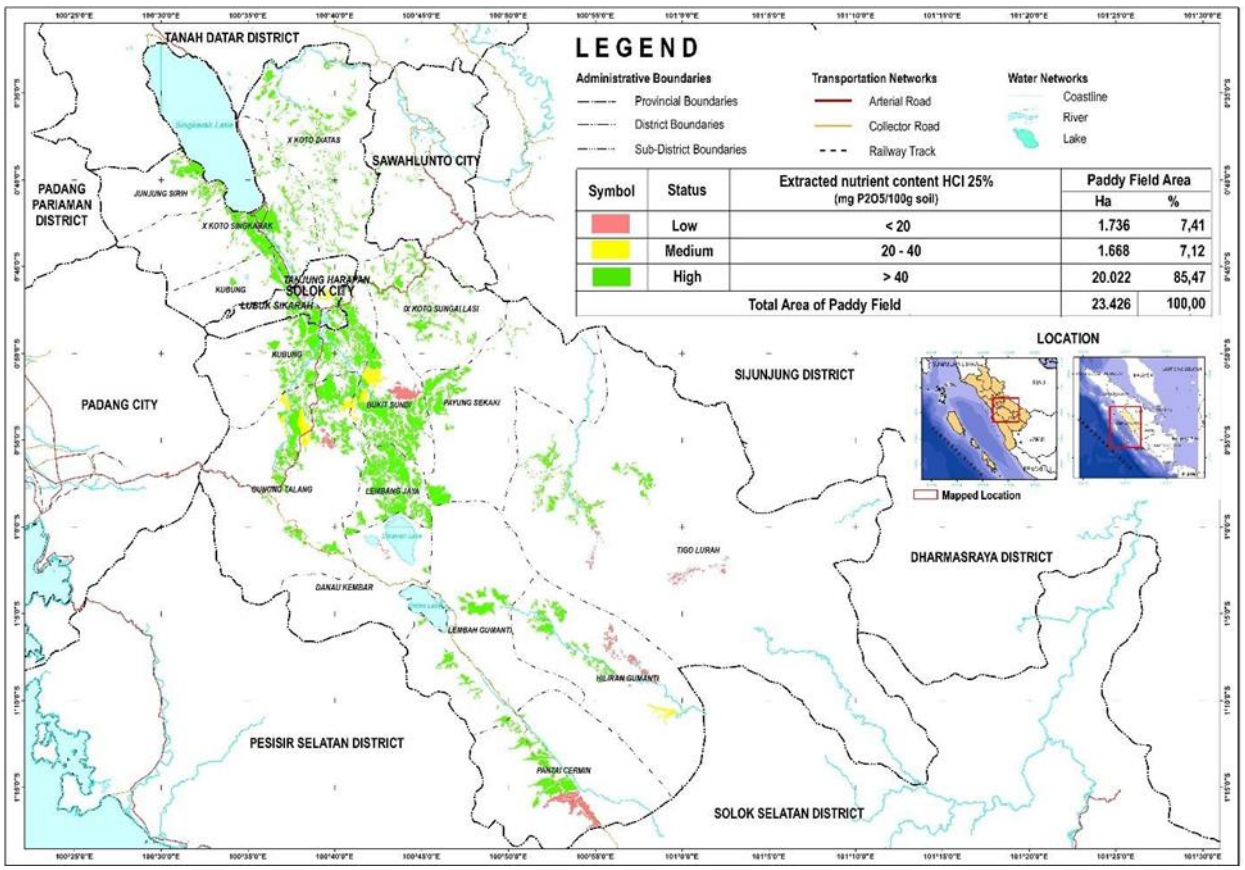


Figure 5. Map of P nutrient status of rice fields in Solok district and city, scale 1:50,000

3.3. Potassium Nutrient Status in Paddy Fields of Solok Regency and Solok City

Based on the results of potassium (K) nutrient status mapping at a 1:50,000 scale, most paddy fields in Solok Regency and Solok City are classified as having high K status. Of the total paddy field area of 23,426 ha, 17,080 ha (72.91%) are categorized as high in K status, while 6,346 ha (27.09%) are classified as moderate. No paddy fields were identified as having low K status (Figure 6).

Potassium (K) accumulation is predominant in paddy fields in Solok Regency and Solok City. This condition occurs when potassium inputs derived from fertilizers, rice straw, organic amendments, and irrigation water exceed potassium outputs through crop harvest, leaching, and surface runoff. In addition to intensive and continuous potassium fertilization, irrigation water also serves as an important source of K in paddy fields. Irrigation water can supply dissolved K ions as well as sediment particles containing potassium; therefore, in long-term technically irrigated paddy systems, it can make a significant contribution to soil K accumulation (Kasno et al., 2021).

Potassium is one of the macronutrients most extensively taken up by rice plants due to its essential role in a wide range of physiological processes. However, in intensive paddy systems with long-term potassium fertilization, not all applied potassium is utilized by the crop. A portion of K is retained in various soil fractions, particularly as exchangeable potassium and non-

exchangeable potassium bound to clay minerals (Lalitha and Dhakshinamoorthy, 2014; Ragel et al., 2019).

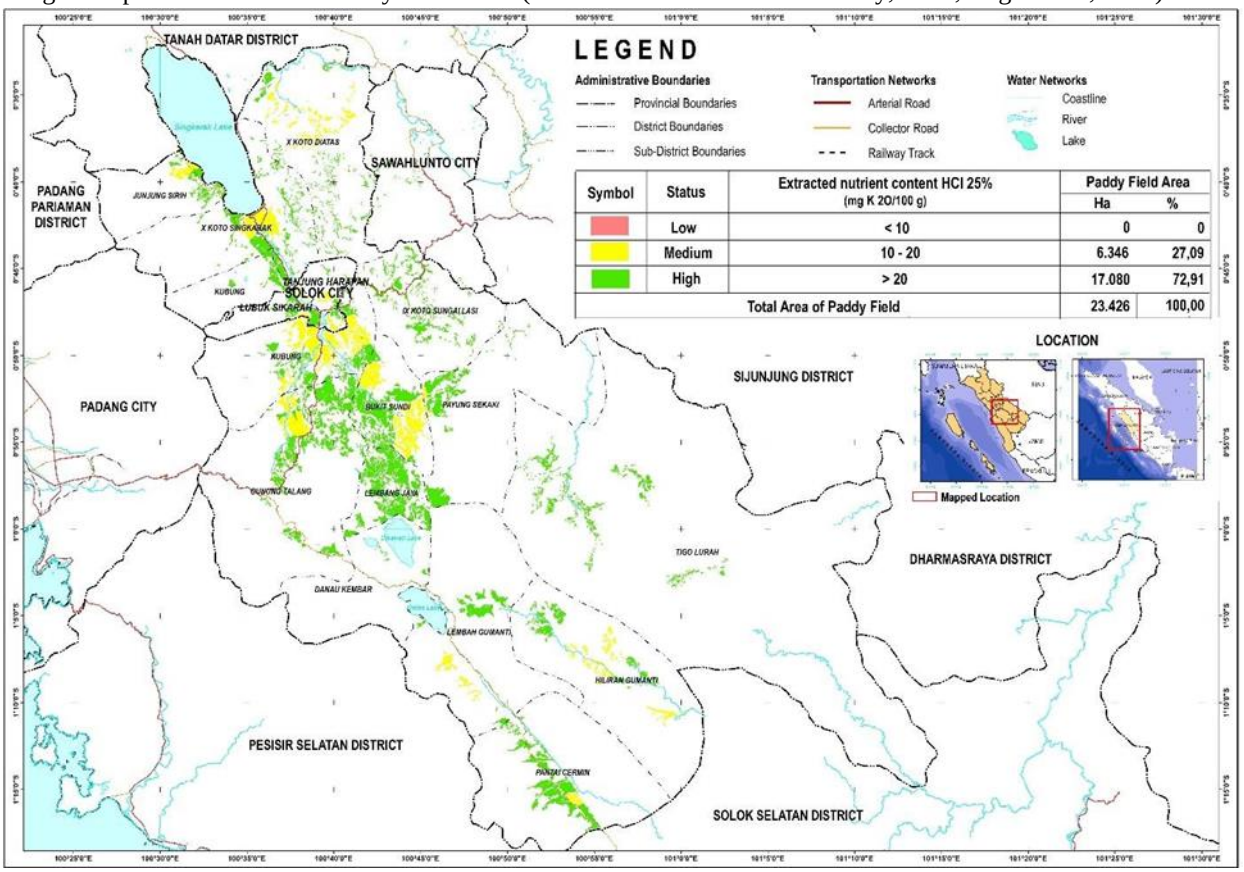


Figure 6. Map of nutrient K status of rice fields in Solok district and city, Scale 1:50,000.

The accumulation of potassium in these two fractions forms a reserve, commonly referred to as legacy potassium, that serves as a long-term nutrient source. The non-exchangeable K fraction acts as a buffer for potassium availability by replenishing (recharging) the soil solution when available K concentrations decline. Studies on paddy soils in Japan have shown that this fraction can supply approximately 10–61% of the potassium requirement of rice crops. These findings indicate that excess potassium resulting from long-term fertilization can be stored in soil minerals and gradually released to meet plant demand. Therefore, non-exchangeable K should be considered in evaluating soil fertility status and in developing potassium fertilization recommendations for intensively managed paddy systems (Mizutani et al., 2024). In paddy fields with high soil P and K status, application of a soil amendment consisting of cattle manure compost, dolomite, and harzburgite increased rice yield by 1.753 t ha^{-1} compared with the unamended treatment (Lenin and Siska, 2018a).

4. Conclusion

Most paddy fields in Solok Regency and Solok City showed low soil organic carbon (SOC) and high P and K status, with 68.24% of the 23,426 ha having low SOC, while 85.47% and 72.91% had high P and K status, respectively. These findings highlight a clear soil fertility imbalance, characterized by SOC depletion and the accumulation of P and K. Therefore, soil fertility management should prioritize rebuilding SOC through appropriate organic amendments while reducing unnecessary P and K inputs and utilizing existing nutrient reserves to improve fertilizer-use efficiency and sustain rice production.

References

Agustina, C., Lutfi Rayes, M., & Kuntari, M. (2020). Pemetaan sebaran status unsur hara N, P, dan K pada lahan sawah di Kecamatan Turen, Kabupaten Malang. *Jurnal Tanah dan Sumberdaya Lahan, 7*, 273-282. https://doi.org/10.21776/ub.jtsl.2020.007.2.11

Aumtong, S., Chotamonsak, C., Pongwongkam, P., & Cantiya, K. (2023). Chemical fertilization alters soil carbon in paddy soil through the interaction of labile organic carbon and phosphorus fractions. *Agronomy, 13*(6), Article 1588. https://doi.org/10.3390/agronomy13061588

Babu, T., Tubana, B., Paye, W., Kanke, Y., & Datnoff, L. (2016). Establishing soil silicon test procedure and critical silicon level for rice in Louisiana soils. *Communications in Soil Science and Plant Analysis, 47*, 1578–1597. https://doi.org/10.1080/00103624.2016.1194996

Bhat, M. A., Mishra, A. K., Shah, S. N., Bhat, M. A., Jan, S., Rahman, S., Baek, K., & Jan, A. T. (2024). Soil and mineral nutrients in plant health: A prospective study of iron and phosphorus in the growth and development of plants. *Current Issues in Molecular Biology, 46*, 5194–5222.

Badan Pusat Statistik. (2023). *Luas panen, produksi, dan produktivitas*

padi menurut provinsi. https://www.bps.go.id/indicator/53/1498/1/luas-panen-produksi-dan-produktivitas-padi-menurut-provinsi.html

Burbey, I., Sahar, A., Mawardi, E., & Azmi, A. (2005). *Pemetaan status hara tanah sawah Kota Padang dan Kabupaten Agam skala 1:50.000* [Laporan hasil penelitian]. Balai Pengkajian Teknologi Pertanian Sumatera Barat.

Chen, S., Gao, J., Chen, H., Zhang, Z., Huang, J., Lv, L., & Tan, J. (2023). The role of long-term mineral and manure fertilization on P species accumulation and phosphate-solubilizing microorganisms in paddy red soils. *SOIL, 9*, 101–116. https://doi.org/10.5194/soil-9-101-2023

Chen, Y., Xu, L., & Zhao, X. (2026). Paddy-upland rotation outperforms upland rotation in enhancing soil nutrient multifunctionality in coastal saline-alkali farmlands through soil aggregate optimization. *Geoderma, 469*, Article 117812. https://doi.org/10.1016/j.geoderma.2026.117812

Dinas Pertanian Kabupaten Solok. (2026). *Data potensi produksi pertanian tahun 2025*.

Fachriansyah, F., Sufardi, S., & Y. D. (2023). Analisis status hara N, P, dan K pada tanah sawah Kecamatan Kuta Baro, Kabupaten Aceh Besar (Analysis of N, P, and K nutrient status in rice fields of Kuta Baro). *Jurnal Ilmiah Mahasiswa Pertanian, 8*, 790–799.

Fang, Y., Deng, H., Gu, H., Cui, X., Liao, S., Lu, Z., Cong, R., Li, X., Ren, T., & Lu, J. (2026). Nutrient management regulates soil fertility in paddy-upland rotations: A meta-analysis. *Journal of Integrative Agriculture*. Advance online publication, 1–22. https://doi.org/10.1016/j.jia.2026.01.020

Gummert, M., Hung, N. V., Chivenge, P., & Douthwaite, B. (2020). *Sustainable rice straw management*. Springer. https://doi.org/10.1007/978-3-030-32373-8

Hayatu, N. G., Liu, Y., Zhang, S., Huang, J., Han, T., Lan, X., Ji, J., & Zhang, H. (2023). Long-term organic manure substitution increases yield and phosphorus use efficiency in a double-rice system by altering soil phosphorus uptake and apparent balance. *Agronomy, 13*, Article 1440. https://doi.org/10.3390/agronomy13061440

Hermansah, Tsugiyuki, M., & Toshiyuku, W. (2009). Nutrient management of sawah in relation to soil characteristics and rice production in West Sumatra, Indonesia. In *Proceedings of the 9th International Conference of the East and Southeast Asia Federation of Soil Science Societies*. Korean Society of Soil Science and Fertilizer.

Husnain, Kasno, A., & Rochayati, S. (2016). Pengelolaan hara dan teknologi pemupukan mendukung swasembada pangan di Indonesia. *Jurnal Sumberdaya Lahan, 10*, 25–36.

Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstić, D., Aslam, Z., Zulfiqar, U., Rauf, A., Hano, C., & El-Esawi, M. A. (2021). Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants, 10*, Article 2001. https://doi.org/10.3390/plants10102001

Ibrahim, M., Iqbal, M., Tang, Y., Khan, S., & Guan, D. (2022). Phosphorus mobilization in plant–soil environments and inspired strategies for managing phosphorus: A review. *Agronomy, 12*, Article 2539. https://doi.org/10.3390/agronomy12102539

Kasno, A. (2010). Nutrient balance at integrated nutrient management on lowland rice which is dominated by 1:1 clay mineral for high potential rice yields. *Jurnal Tanah Tropika (Journal of Tropical Soils), 15*, 119–126. https://doi.org/10.5400/jts.2010.15.2.119

Kasno, A., Setyorini, D., Widowati, L. R., & Rostaman, T. (2021). Evaluasi karakteristik, sumbangan hara K air irigasi dan jerami serta respons pemupukan hara kalium pada lahan sawah (Characteristics evaluation, nutrient contribution of irrigation water and straw toward response to nutritional potassium fertilization). *Jurnal Ilmu Pertanian Indonesia, 33*, 189–198.

Koushika, S. P., Krishnaveni, A., Pazhanivelan, S., Arunkumar, V., & Devaki, P. (2024). Carbon economics of different agricultural practices. *arXiv*. https://doi.org/10.48550/arXiv.2403.07530

Kusmiyarti, T. B., Mega, M., & Dibia, D. W. (2005). Kajian sebaran humus, alofan dan senyawa humus kompleks pada tanah Andisol. *Planta Tropika, 1*, 61–65.

Ladha, J., Peoples, M., Reddy, P., Biswas, J., Bennett, A., Jat, M., & Krupnik, T. (2022). Biological nitrogen fixation and prospects for ecological intensification in cereal-based cropping systems. *Field Crops Research, 283*, Article 108541. https://doi.org/10.1016/j.fcr.2022.108541

Lalitha, M., & Dhakshinamoorthy, M. (2014). Forms of soil potassium—A review. *Agricultural Reviews, 35*, 64–68. https://doi.org/10.5958/j.0976-0741.35.1.008

Lenin, I. (2016). Kajian pemupukan fosfor pada tiga tingkat status fosfor tanah terhadap tanaman padi sawah di Kabupaten Dharmasraya, Sumatera Barat. *Jurnal Pengkajian dan Pengembangan Teknologi Pertanian, 19*, 71–78.

Lenin, I., & Siska, W. (2018a). Formulasi pembenah tanah untuk meningkatkan hasil padi di lahan sawah Kabupaten Sijunjung, Sumatera Barat. *Jurnal Pengkajian dan Pengembangan Teknologi Pertanian, 21*, 113–126.

Lenin, I., & Siska, W. (2018b). Pengaruh residu pupuk P pada MT I terhadap status P tanah dan hasil padi sawah pada MT II di Kabupaten Dharmasraya. *Jurnal Pengkajian dan Pengembangan Teknologi Pertanian, 21*, 63–72. https://doi.org/10.21082/jpptp.v21n1.2018.p63-72

Lenin, I., Siska, W., & Mirnia, E. (2021). The effect of straw compost on nutrient uptake and yield of rice in newly opened and intensive lowland. *E3S Web of Conferences, 306*, Article 01032. https://doi.org/10.1051/e3sconf/202130601032

Liu, X., Han, R., Cao, Y., Turner, B. L., & Ma, L. Q. (2022). Enhancing phytate availability in soils and phytate-P acquisition by plants: A review. *Environmental Science & Technology, 56*, 9196–9219. https://doi.org/10.1021/acs.est.2c00099

Martinengo, S., Schiavon, M., Santoro, V., Said, D., & Marco, P. (2023). Assessing phosphorus availability in paddy soils: The importance of integrating soil tests and plant responses. *Biology and Fertility of Soils*, 391–405. https://doi.org/10.1007/s00374-023-01714-8

Maulana, M. (2004). Peranan luas lahan, intensitas pertanaman dan produktivitas sebagai sumber pertumbuhan padi sawah di Indonesia 1980–2001. *Jurnal Agro Ekonomi, 22*, 74–95.

Menezes-Blackburn, D., Giles, C., Darch, T., George, T. S., Blackwell, M., Stutter, M., Shand, C., Lumsdon, D., Cooper, P., & Haygarth, P. M. (2018). Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: A review. *Plant and Soil, 427*, 5–16. https://doi.org/10.1007/s11104-017-3362-2

Mizutani, Y., Kubotera, H., Fujii, T., Maeda, T., & Hiradate, S. (2024). Recharge of exchangeable K from non-exchangeable fractions as affected by exchangeable K and K acquisition by rice in Japanese paddy soils. *Soil Science and Plant Nutrition, 70*, 295–305. https://doi.org/10.1080/00380768.2024.2357099

Naorem, A., Jayaraman, S., Sinha, N. K., Mohanty, M., Chaudhary, R. S., Hati, K. M., Mandal, A., Thakur, J. K., Patra, A. K., Srinivasarao, C., Chaudhari, S. K., Dalal, R. C., & Lal, R. (2023). Eight-year impacts of conservation agriculture on soil quality, carbon storage, and carbon emission footprint. *Soil and Tillage Research, 232*, Article 105748. https://doi.org/10.1016/j.still.2023.105748

Palihakkara, J., Burkitt, L., Jeyakumar, P., & Attanayake, C. P. (2024). Exploring phosphorus dynamics in submerged soils and its implications on the inconsistent rice yield response to added inorganic phosphorus fertilisers in paddy soils in Sri Lanka. *Journal of Soil Science and Plant Nutrition, 24*, 1–20. https://doi.org/10.1007/s42729-023-01553-4

Ragel, P., Raddatz, N., Leidi, E. O., Quintero, F. J., & Pardo, J. M. (2019). Regulation of K^+ nutrition in plants. *Frontiers in Plant Science, 10*, Article 281. https://doi.org/10.3389/fpls.2019.00281

Saidy, A. R. (2018). *Bahan organik tanah: Klasifikasi, fungsi dan metode studi*. Lambung Mangkurat University Press.

Sanchis Jiménez, E., Ferrer Roglán, M., Calvet Sanz, S., Coscollà, C., Yusà, V., & Cambra López, M. (2014). Gaseous and particulate emission profiles during controlled rice straw burning. *Atmospheric Environment, 98*, 25–31. https://doi.org/10.1016/j.atmosenv.2014.07.062

Schaller, J., Wu, B., Amelung, W., Hu, Z., Stein, M., & Lehndorff, E. (2022). Silicon as a potential limiting factor for phosphorus availability in paddy soils. *Scientific Reports, 12*, Article 20805. https://doi.org/10.1038/s41598-022-20805-4

Sembiring, H., Subekti, N. A., Nugraha, D., Priatmojo, B., & Stuart, A. M. (2020). Yield gap management under seawater intrusion areas of Indonesia to improve rice productivity and resilience to climate change. *Agriculture, 10*(1), Article 1. https://doi.org/10.3390/agriculture10010001

Sukarman, Setyorini, D., & Ritung, S. (2012). Metodologi percepatan pemetaan status hara lahan sawah. In I. P. Wigena, N. L. Nurida, D. Setyorini, Husnain, E. Husen, & E. Suryani (Eds.), *Teknologi pemupukan dan pemulihan lahan terdegradasi* (pp. 141–149). Badan Penelitian dan Pengembangan Pertanian, Kementerian Pertanian.

Sulaeman, Y., Aryati, V., Suprihatin, A., Santari, P. T., Haryati, Y., Susilawati, S., Siagian, D. R., Karolinoerita, V., Cahyaningrum, H., Pramono, J., Wulanningtyas, H. S., Fauziah, L., Raharjo, B., Syafruddin, S., Cahyana, D., Waluyo, W., Susanto, B., Purba, R., Dewi, D. O., ... Azis, A. (2024). Yield gap variation in rice cultivation in Indonesia. *Open Agriculture, 9*, 1–13.

Sullivan, L. O., Holloway, P., Wall, D., Bondi, G., & Castell, A. (2026). Impact of management intensity of agricultural systems and soil intrinsic characteristics on soil organic carbon stocks. *Agriculture, Ecosystems & Environment, 410*, Article 110547. https://doi.org/10.1016/j.agee.2026.110547

Supriyadi, Pratiwi, M. K., Minardi, S., & Prastiyaningsih, N. L. (2020). Carbon organic content under organic and conventional paddy field and its effect on biological activities: A case study in Pati Regency, Indonesia. *Caraka Tani: Journal of Sustainable Agriculture*, *35*, 108–116. https://doi.org/10.20961/carakatani.v35i1.34630

Supriyadi, Ustiatik, R., Mukti, B., Minardi, S., Widijanto, H., Bima, M., & Sakti, G. (2022). Soil quality status under Hazton's paddy farming: A case study in Banyumas Regency, Indonesia. *SAINS TANAH: Journal of Soil Science and Agroclimatology, 19*, 123–131.

Suryani, E., Subandiono, R. E., Yatno, E., Hikmat, M., Husnain, & Anda, M. (2021). Variability of soil mineralogical composition in Sentra Bareh Solok paddy field as affected by eruption material from Mt. Talang. In *IOP Conference Series: Earth and Environmental Science, 648*, Article 012042. https://doi.org/10.1088/1755-1315/648/1/012042

Syofyan, A., M. S., Nurjaya, & J. S. (2000). *Laporan akhir penelitian status hara P dan K lahan sawah sebagai dasar penggunaan pupuk yang efisien pada tanaman pangan.*

Syofyan, A., Nurjaya, & A. K. (2004). Status hara tanah sawah untuk rekomendasi pemupukan. In F. Agus, A. Admiharja, S. Harjowigeno, A. Fagi, & W. Hartatik (Eds.), *Tanah sawah dan teknologi pengelolaannya* (pp. 83–114). Pusat Penelitian dan Pengembangan Tanah dan Agroklimat.

Voltr, V., Menšík, L., Pospíšilová, L., Hlisnikovský, L., Hruška, M., & Pokorný, E. (2021). The soil organic matter in connection with soil properties and soil inputs. *Agronomy, 11*(4), Article 779. https://doi.org/10.3390/agronomy11040779

Wahyunto, & Dariah, A. (2014). Degradasi lahan di Indonesia: Kondisi existing, karakteristik, dan penyeragaman definisi mendukung gerakan menuju satu peta (Indonesian degraded peatland: Existing condition, its characteristics and standardized definition to support One Map Policy Movement). *Jurnal Sumberdaya Lahan, 8*, 81–93.

Wahyunto, Hikmatullah, Suryani, E., C., T., Ritung, S., Mulyani, A., Sukarman, Nugruho, K., Sukarman, Nugroho, K., Sulaeman, Y., Suparto, Subandiono, R., Sutriadi, T., & Nursyamsi, D. (2016). *Petunjuk teknis pedoman survei dan pemetaan tanah tingkat semi detail skala 1:50.000*. Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian, Badan Penelitian dan Pengembangan Pertanian.

Wang, H., Wang, S., Yu, Q., Zhang, Y., Wang, R., Li, J., & Wang, X. (2020). No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. *Journal of Environmental Management, 261*, Article 110261. https://doi.org/10.1016/j.jenvman.2020.110261

Wang, X., Zheng, H., Wu, L., Ding, X., & Lu, T. (2023). Responses of soil organic and inorganic carbon to organic and phosphorus fertilization in a saline-alkaline paddy field. *Geoscience Letters, 10*, Article 1. https://doi.org/10.1186/s40562-023-00268-9

Wihardjaka, A., & Harsanti, E. S. (2020). Dukungan pupuk organik untuk memperbaiki kualitas tanah pada pengelolaan padi sawah ramah lingkungan. *Jurnal Pangan, 30*, 53–64.

Yatno, E., & Suharta, N. (2011). Andisols derived from acid pyroclastic liparite tuff: Their properties and their management strategy for agricultural development. *Jurnal Tanah dan Iklim, 33*, 49–64.

Yu, C., Kao, P., & Wang, S. (2026). The availability of legacy phosphorus for rice growth in phosphorus-rich paddy soils: A two-season case study. *Agronomy, 16*, 1–16.

Zhang, N., Bai, L., Wei, X., Li, T., Tang, Y., Wen, J., Peng, Z., Zhang, Y., Wang, Y., Zeng, X., & Su, S. (2025). Effects of organic material addition on carbon cycling and soil fertility in paddy soil. *Journal of Environmental Management, 379*, Article 124898. https://doi.org/10.1016/j.jenvman.2025.124898

Zhou, W., Lv, T., Chen, Y., Westby, A. P., & Ren, W. (2014). Soil physicochemical and biological properties of paddy-upland rotation: A review. *The Scientific World Journal, 2014*, Article 856352. https://doi.org/10.1155/2014/856352