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# Application of rice straw and corn straw compost for enhancing phosphorus availability in ultisol and corn plants

Kasifah Kasifah [a,*], Muhammad Roil Bilad [b], Sumbangan Baja [c]

[a] Faculty of Agriculture, Universitas Muhammadiyah Makassar, Jl. Sultan Alauddin No. 259, Makassar, Indonesia
[b] Faculty of Integrated Technologies, Universiti Brunei Darussalam, Jalan Tungku Link, BE1410, Brunei
[c] Soil Science Departement, Faculty of Agriculture, Hasanuddin University, Jl. Perintis Kemerdekaan, Tamalanrea, Makassar, Indonesia

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ABSTRACT

Ultisol, a widely distributed soil in tropical regions, remains underutilized in agriculture due to its inherently low phosphorus (P) availability, with substantial amounts bound in recalcitrant Al-P, Fe-P, and Ca-P fractions, limiting plant uptake. However, limited understanding exists regarding how different compost sources can more effectively mobilize these P fractions to enhance crop performance in field-relevant tropical conditions. This study addressed this problem by evaluating the efficacy of rice straw and corn stover composts in transforming these key P fractions into more available forms for corn (*Zea mays*) growth. A two-phase experimental design was employed, including a six-week soil incubation where Ultisol was amended at 20 tons/ha to assess shifts in Al-P, Fe-P, Ca-P, and available P, and a subsequent greenhouse experiment examining corn growth responses to varying compost rates (10, 20, 30 tons/ha). Compared to rice straw compost, corn stover compost, which contained higher levels of humic and fulvic acids, more effectively reduced P bound in Al-P, Fe-P, and Ca-P complexes by up to 67 %, thereby significantly enhancing P availability. These results align with previous findings on organic amendments but further demonstrate the pivotal role of higher humic and fulvic acid content in boosting P release from multiple soil-bound fractions. Enhanced P availability translated into improved crop performance, as evidenced by increased ear length, diameter, and grain weight. The implications of this study suggest a cost-effective and environmentally friendly approach to overcoming P limitations in acidic, highly weathered soils. Nonetheless, the greenhouse-scale scope represents a limitation, highlighting the need for longer-term field evaluations to assess broader impacts on soil health and nutrient cycling. These findings highlight that the superior capacity of corn stover compost to chelate metal ions, release bound P, and increase its bioavailability offers a sustainable strategy to overcome P limitation in Ultisol. Future research should explore multi-season field trials and in-depth microbial assessments of compost impacts on P dynamics, soil health, and crop resilience, ultimately optimizing sustainable soil management in tropical agriculture.

## 1. Introduction

Phosphorus (P) deficiency in tropical soils significantly hinders agricultural productivity and threatens global food security (Montalvo et al., 2018). In highly weathered tropical soils such as Ultisol, the inherently low P availability often stems from complex interactions between soil acidity, mineral composition, and extensive leaching, leading to P fixation and reduced crop yields (Montalvo et al., 2018). Given that around 70 % of the global population depends on agriculture, nutrient limitations in these soils present substantial risks to food security and price stability (Graaf et al., 2019). In Indonesia, Ultisol covers approximately 18 million hectares, notably across Sumatra, Java, and Sulawesi. This soil, representing about 8 % of the world's land area, has significant agricultural potential due to its water retention capacity and mineral-rich composition (Pasang et al., 2019; Gupta et al., 2020). Despite its mineral richness, Ultisol is often regarded as "dead soil" due to limited P bioavailability, acidic conditions, and elevated levels of Al and Fe that restrict P solubility (Gupta et al., 2020; Lukmansyah et al., 2020). These constrains contribute to underutilization of arable land (Lukmansyah et al., 2020).

Although acidic soils predominantly fix P through Al and Fe complexes, Ca-P may also persist when calcium-rich parent materials are

* Corresponding author.
*E-mail address:* kasifah@unismuh.ac.id (K. Kasifah).

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present, thus maintaining significant Ca-P fractions even under acidic conditions (Pasang et al., 2019; Gupta et al., 2020; Lukmansyah et al., 2020; Chulo et al., 2021). Much of this P is bound in Al-P, Fe-P, and Ca-P complexes that limit plant accessibility (Simpson et al., 2011). Additionally, microbial communities adapt to exploit more recalcitrant substrates, potentially exacerbating low P bioavailability (Yao et al., 2018). Such conditions can reduce ecosystem resilience and biodiversity, ultimately affecting ecosystem services critical to agriculture (Xu et al., 2016).

A promising strategy to improve P availability in Ultisol involves organic amendments like compost. Organic matter from sources such as rice straw or corn stover compost can supply organic acids—particularly humic and fulvic acids—that chelate metal ions and enhance P release (Lansari et al., 2018; Sootahar et al., 2019). Studies report that rice straw compost can increase available P by up to 30 % (Reyes-Bozo et al., 2014), while humic and fulvic acids have been shown to improve P solubility by up to 40 % in acidic soils (Ekpo et al., 2016; Graaf et al., 2019). These acids interact with Al, Fe, and Ca ions, altering soil chemistry and promoting favorable conditions for P release (Ekpo et al., 2016). Furthermore, organic amendments have been linked to improved plant development and yield in P-deficient soils (Adusei et al., 2017).

Despite these documented benefits, gaps remain in understanding the specific mechanisms by which compost, particularly from local biomass sources, transforms P fractions in Ultisol (Pasang et al., 2019; Gupta et al., 2020; Lukmansyah et al., 2020; Lansari et al., 2018). Moreover, existing research has not fully explored how different compost types specifically target Al-P, Fe-P, and Ca-P complexes in highly weathered soils, nor has it thoroughly assessed whether certain biomass sources can yield greater P availability for crops. Investigating how compost disrupts Al-P, Fe-P, and Ca-P complexes will help optimize its application. Accordingly, this study addresses a critical knowledge gap: the comparative effectiveness of rice straw vs. corn stover composts in mobilizing P to support crop productivity in Ultisol. We hypothesize that corn stover compost, richer in humic and fulvic acids, more effectively mobilizes bound P than rice straw compost, enhancing P availability and uptake by maize (Zea mays). Thus, this study aims to elucidate how these composts influence P fractionation and availability in Ultisol, guiding sustainable soil management in tropical agriculture.

## 2. Materials and methods

This study was conducted in two phases to evaluate the impact of rice straw and corn stover composts on P dynamics in Ultisol soil and the subsequent effects on corn (*Zea mays*) growth. To ensure data quality, all experiments were performed in triplicate, and instruments used for chemical analyses were calibrated against certified reference materials prior to each measurement. The first phase involved a controlled six-week laboratory incubation to assess changes in P fractions. The second phase was a greenhouse experiment examining corn growth responses to varying compost rates. All sampling procedures followed standard sterilization protocols, and each soil or plant sample was handled in a way to prevent cross-contamination (e.g., using separate, sterile stainless-steel scoops for each treatment).

### *2.1. Compost preparation and characterization*

Rice straw and corn stover were collected from agricultural fields in Maros Regency, South Sulawesi, Indonesia. The collected plant residues were air-dried to reduce moisture content to approximately 15 %. Composting was conducted following standard aerobic composting procedures (Stevenson, 1994). All biomass samples were processed in triplicate batches to cross-verify consistency in compost composition.

#### *2.1.1. Composting process*

For each compost type, 500 kg of dried biomass was mixed with cow manure at a ratio of 3:1 (biomass, w/w) (Paramisparam et al., 2021). The mixture was formed into windrows (1.5 m height, 2 m width, 3 m length). During composting, temperature was recorded with a calibrated compost thermometer ( ± 1°C accuracy), and moisture content was measured by gravimetric analysis in triplicate samples from different points in the pile. Moisture content was adjusted to 60 % using deionized water, and piles were turned every five days to maintain aerobic conditions. The process lasted 60 days with temperature (50°C–60°C) and moisture monitored regularly (Urra et al., 2019; Kim et al., 2022). Maturity was determined by temperature stabilization, C/N ratio $<$ 20, and absence of unpleasant odors (Stevenson, 1994).

#### *2.1.2. Compost analysis*

Samples of matured compost were analyzed for pH (1:5 w/v), total N (Kjeldahl), organic C (Walkley-Black), total P (acid digestion + molybdenum blue), K, Ca, Mg, Na (flame photometry, AAS), and humic and fulvic acids (Stevenson, 1994; Rahmi et al., 2018). Each parameter was measured in triplicate, and mean values were reported alongside standard deviations to confirm analytical precision. Where applicable, blanks and Certified Reference Materials (CRMs) were included in each batch to ensure data accuracy. Results are shown in Table 1.

### *2.2. Soil sampling and characterization*

Ultisol soil samples were collected from an uncultivated field in Maros Regency (5°8′52.21" S, 119°33’53.45" E) to ensure minimal prior fertilizer influence. The site was selected based on its representative Ultisol properties and accessibility. Soil samples were taken from the top 0–20 cm layer using a soil auger. A composite sample was created by collecting soil from 10 random points within the field to achieve homogeneity (Hasbullah et al., 2020). All composite subsamples were then pooled and thoroughly mixed, and each final composite was split into triplicates for subsequent analysis to verify data consistency. The samples were air-dried in the shade to preserve soil properties and passed through a 2 mm sieve to remove debris.

Initial soil properties were determined to establish a baseline. Each analysis was conducted in triplicate to ensure methodological reliability, including soil texture (hydrometer method), pH (1:1 soil-to-water ratio), organic matter (Walkley-Black method), cation exchange capacity (CEC) (ammonium acetate method), total nitrogen (Kjeldahl method), available P (Bray I method), and exchangeable aluminum and iron (extracted with 1 M KCl and measured by atomic absorption spectrophotometry) (Gupta et al., 2020).

### *2.3. Laboratory incubation experiment (Phase I)*

A Completely Randomized Design with three treatments and three replications was used: U0 (control, no compost), URC (rice straw compost, 20 t/ha), UCS (corn stover compost, 20 t/ha). Approximately 6.67 g of compost was thoroughly mixed per kg of soil to achieve the field-equivalent rate. Each treatment was prepared in separate labeled pots to prevent cross-contamination, and the mixing procedure was repeated for all replicates to ensure uniform distribution of compost in

**Table 1**
Nutritional analysis of the composts prepared in this study.

| Parameter (unit) | Rice Straw Compost | Corn Straw Compost |
|---|---|---|
| pH | 7.6 | 7.3 |
| Total N (%) | 1.84 | 2.98 |
| Organic C (%) | 18.87 | 20.57 |
| Total P (%) | 0.28 | 0.56 |
| K (%) | 0.86 | 1.47 |
| Ca (%) | 1.25 | 1.32 |
| Mg (%) | 0.60 | 0.89 |
| Na (%) | 1.37 | 1.67 |
| Humic Acid (ppm) | 2181 | 2278 |
| Fulvic Acid (ppm) | 1621 | 1777 |

the soil. Soil moisture was maintained at 60 % field capacity with deionized water (Sukitprapanon et al., 2021). Pots were covered with perforated plastic and incubated at 25°C–30°C for six weeks. Weekly soil samples were collected in triplicate using a sterile stainless-steel scoop, sealed in labeled bags, and immediately stored at 4°C until laboratory analysis to minimize potential microbial or chemical alterations.

Soil samples were analyzed to determine total P, P fractions (including aluminum-bound P, iron-bound P, and calcium-bound P), available P, and pH. Total P, labeled as P-total, was measured by digesting soil samples with concentrated sulfuric acid ($H_2SO_4$) and hydrogen peroxide ($H_2O_2$), followed by colorimetric analysis using the molybdenum blue method as described by Hasbullah et al. (2020). All measurements were run alongside blank and standard solutions to ensure accuracy, and each sample was analyzed in triplicate with relative standard deviations kept below 5 %. P fractionation was conducted through a sequential extraction method proposed by Pierzynski (2009). This process included the extraction of aluminum-bound P (Al-P) using a 0.5 M ammonium fluoride ($NH_4F$) solution at pH 8.2, followed by iron-bound P (Fe-P) extraction with 0.1 M sodium hydroxide (NaOH) after Al-P removal, and finally calcium-bound P (Ca-P) extraction with 0.25 M sulfuric acid ($H_2SO_4$) following Fe-P extraction. The P concentration in each extract was quantified using UV–VIS spectrophotometry at a wavelength of 693 nm, as per Pierzynski's guidelines (2009). Available P, or P-available, was measured using the Bray I method, which is suitable for acidic soils, with absorbance read at 882 nm (Pierzynski, 2009). Soil pH was assessed in a 1:1 soil-to-water suspension using a calibrated pH meter, following the method by Rahmi et al. (2018).

### 2.4. Greenhouse experiment (Phase II)

Based on Phase I results, corn stover compost was selected for the greenhouse experiment with a Completely Randomized Design: P0 (control), P1 (10 t/ha), P2 (20 t/ha), P3 (30 t/ha). Compost was thoroughly mixed at 3.33 g, 6.67 g, and 10 g per kg soil for P1, P2, and P3, respectively (as shown in Table 2). Each compost rate treatment was prepared and replicated three times, ensuring that randomization was maintained to minimize experimental bias. Two seeds of sweet corn (*Zea mays* L. var. Gumarang) were sown and thinned to one plant after germination. Soil moisture was maintained at ~60 % field capacity (Ojo et al., 2018).

At harvest, which occurred 100 days after planting, several parameters were measured to assess soil and plant health as well as crop performance. The available P in the soil was evaluated by collecting soil samples, which were then analyzed using the Bray I method as outlined by Pierzynski (2009). To ensure consistency, soil samples were collected at multiple points within each pot, combined, and analyzed in triplicate. P uptake was assessed by collecting plant tissues, including leaves, stems, and grains, which were oven-dried at 70°C until a constant weight was achieved. These samples were then ground and digested with a nitric-perchloric acid mixture, and the P concentration was subsequently determined colorimetrically using the molybdenum blue method, following the procedure described by Cui et al. (2019). Additionally, agronomic parameters, such as ear length, ear diameter, and dry grain weight per ear, were measured to evaluate the impact of compost on crop performance.

**Table 2**
Treatments applied in the greenhouse experiment.

| Treatment | Compost Type | Application Rate (t/ha) | Equivalent (g/kg soil) |
|---|---|---|---|
| P0 | None (Control) | 0 | 0 |
| P1 | Corn Stover Compost | 10 | 3.33 |
| P2 | Corn Stover Compost | 20 | 6.67 |
| P3 | Corn Stover Compost | 30 | 10 |

### 2.5. Statistical analysis

Data were analyzed using SPSS Statistics version 21 (IBM Corp., Armonk, NY, USA). An Analysis of Variance (ANOVA) was performed to assess the significance of treatment effects at $p < 0.05$ (Hamidi et al., 2021). Prior to ANOVA, data were checked for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test). Tukey's Honest Significant Difference test was used for post-hoc comparisons when significant differences were detected. Additionally, effect sizes were calculated for significant results to better quantify the practical impact of the treatments. Correlation and regression analyses were conducted to examine relationships between compost application rates, P fractions, and plant growth parameters. Graphs were produced with Microsoft Excel.

## 3. Results

### 3.1. Nutritional content of the prepared composts

The chemical analysis of rice straw compost and corn stover compost used in this study is presented in Table 1. Both compost types had slightly alkaline pH levels, with rice straw compost at 7.6 and corn stover compost at 7.3. Corn stover compost was richer in total P, humic acids, and fulvic acids, indicating its potentially stronger influence on P mobilization. These results align with prior findings that link higher humic and fulvic acid content to enhanced nutrient release in acidic soils (Ekpo et al., 2016; Graaf et al., 2019). Corn stover compost exhibited higher concentrations of key nutrients compared to rice straw compost: nitrogen (2.98 % vs. 1.84 %), organic carbon (20.57 % vs. 18.87 %), and total P (0.56 % vs. 0.28 %). Potassium, calcium, magnesium, and sodium were significantly higher in corn stover compost. Moreover, corn stover compost contained higher levels of humic acid (2278 ppm) and fulvic acid (1777 ppm), crucial for improving soil properties. Such nutrient enrichment underscores corn stover compost's potential for improving Ultisol fertility, though future research could verify this across broader soil types. These findings suggest that corn stover compost may have a greater impact on nutrient dynamics and P availability in Ultisol when compared to rice straw compost.

### 3.2. Soil pH dynamics

The application of compost notably influenced the pH levels of Ultisol during the incubation period, as shown in Fig. 1. Initially, both compost treatments led to a decline in soil pH within the first two weeks, indicating increased acidity after adding organic matter. This trend stabilized in the subsequent weeks, with minimal pH fluctuations observed until the end of the six-week incubation period. Such a transient decrease in pH is consistent with other studies that have reported initial acidification due to organic acid production (Wu et al., 2019; Chen et al., 2021a, 2021b). The initial decrease in soil pH was likely attributed to organic acids in the composts, such as humic and fulvic acids. These acids release protons from their carboxylate, aliphatic, and phenolic groups, consequently releasing hydrogen ions ($H^+$) into the soil solution, aligning with research findings by Rahmi et al. (2018), Wu et al. (2019), and Chen et al. (2021a, 2021b). Fulvic acids, in particular, played a more substantial role in soil acidity due to their higher carboxyl group content than humic acids. Fulvic acids' higher carboxyl group content likely intensified these early pH shifts. However, because the pH eventually stabilized, it suggests that Ultisol's buffering capacity and the gradual decomposition of organic acids likely mitigated long-term soil acidification.

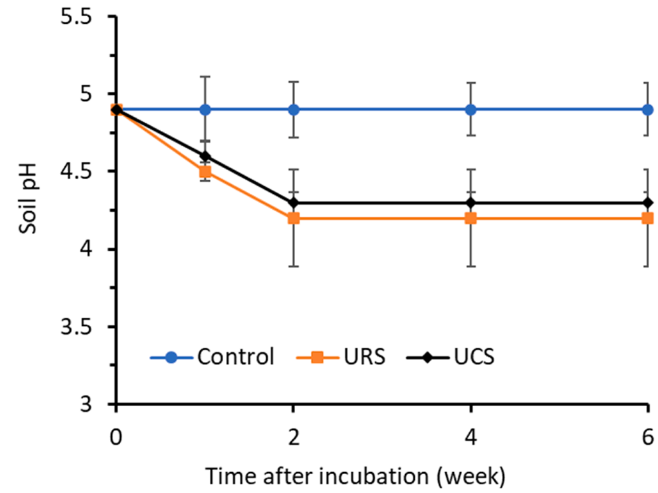


**Fig. 1.** The soil pH during incubation of ultisol (Control), and its combination with rice straw (URC, dosed at 20 ta/ha) and corn straw compost (UCS, dosed at 20 ta/ha).

### 3.3. Total phosphorus dynamics

As shown in Fig. 2, the P-total content in Ultisol decreased steadily during the six-week incubation period for rice straw and corn stover compost treatments. Meanwhile, the control group displayed minimal fluctuations in total P levels. This steady reduction implies that applying composts likely facilitated the transformation of total P into more labile, plant-accessible forms. This reduction suggests that the compost application supported the conversion of total P into more accessible forms. The decline observed aligns with organic amendments' function in boosting P mobility and availability in soil by stimulating P release from stable complexes, as reported by Sukitprapanon et al. (2021). These findings are also consistent with studies indicating that organic acids from compost enhance P desorption and mineral dissolution in highly weathered soils (Liu et al., 2018; Tripathy et al., 2021). Nonetheless, a key limitation of this analysis is that it was confined to a controlled incubation setting; future field trials could validate these results under more variable environmental conditions.

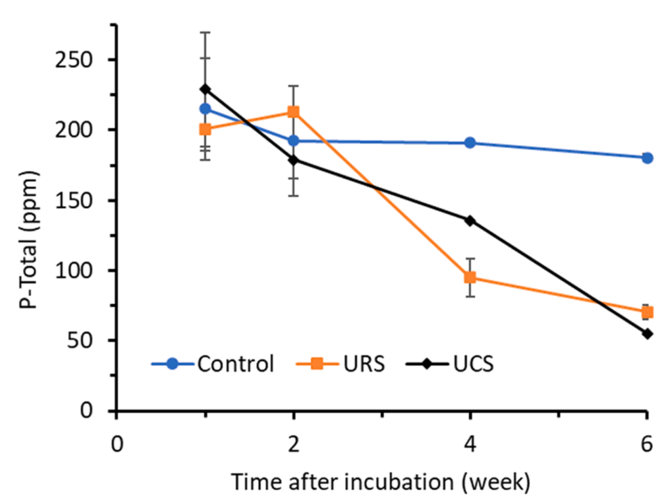


**Fig. 2.** Total P of ultisol (Control) and its combination with rice straw (URC, dosed at 20 ta/ha) and corn straw compost (UCS, dosed at 20 ta/ha).

### 3.4. Phosphorus forms and plant uptake potential

#### 3.4.1. Aluminum-bound phosphorus

P fractionation analysis revealed a significant decrease in Aluminum-bound (Al-P) following the application of compost, as depicted in Fig. 3**A**. Rice straw compost led to a 20.26 % reduction in Al-P, while corn stover compost resulted in a more substantial decrease of 35.41 %. The more pronounced decline observed with corn stover compost underscores the potential importance of its higher humic and fulvic acid content for breaking Al-P bonds. Such acids bind aluminium ions, diminishing their ability to form Al-P complexes, consistent with findings by Hiradate et al. (2007) and Yang et al. (2022). The chemical reaction responsible for this change is shown below. This reaction depicts the release of phosphate ions into the soil and thus enhancing P accessibility for plants. From a methodological perspective, these fractionation analyses were performed in triplicate with strong reproducibility (RSD <5 %), indicating robust data quality.

$Al(Fe)(H_2O)_3(OH)_2H_2PO_4$ + Chelate → $PO_4^{2-}$ (soluble) + complex Al-Fe-Chelate

#### 3.4.2. Iron-bound phosphorus

Fig. 3**B** shows the changes in Fe-bound P (Fe-P) during the incubation. The reduction in Fe-P was more significant in rice straw compost (41.82 %) than in corn stover compost (39.07 %). The decrease could be attributed to the release of P from Fe-P complexes for enhanced plant uptake, highlighting the advantage of compost in improving the availability of soil nutrition for plant growth. This finding slightly diverges from the Al-P reduction results, where corn stover compost was more effective, suggesting that the specific composition of each compost might differentially target Fe-bound and Al-bound P pools. Humic and fulvic acids interacting with iron to create stable organo-metal complexes hindered P re-adsorption, promoting its release into the soil solution (Rahmi et al., 2018; Yang et al., 2022). A strong correlation exists between compost incubation time and Fe-P reduction, as evidenced by $R^2$ values of 0.7839 for rice straw compost and 0.9197 for corn stover compost, underscoring the significance of the incubation duration in the P release process. However, these correlations also imply that a prolonged incubation period could lead to further Fe-P reduction, a hypothesis warranting extended studies or field-scale trials.

#### 3.4.3. Calcium-bound phosphorus

Fig. 3C illustrates the changes in Ca-bound P (Ca-P) dynamics post-compost application. Rice straw and corn stover composts notably reduced Ca-P levels in Ultisol, with reductions of 60.57 % and 67.35 %, respectively. These percentages align with Ojo et al. (2018), who reported similar Ca-P dissolution rates in acidic soils amended with organic substrates. The sharp initial decline during the first two weeks suggests rapid complexation by organic acids, enhancing Ca-P solubility. The increased solubility of Ca-P under acidic conditions was amplified by organic acids in the compost, such as humic and fulvic acids. These acids chelate calcium ions, facilitating the dissolution of Ca-P (Ojo et al., 2018). Correlation analyses support this, revealing $R^2$ values of 0.99 for rice straw compost and 0.99 for corn stover compost, indicating near-perfect linearity between compost application and Ca-P reduction. Such strong correlations highlight the reliability of the fractionation approach but also suggest that verifying these findings under field conditions and over multiple growing seasons would be beneficial for establishing long-term trends.

#### 3.4.4. Available phosphorus (P-available)

The available P (P-available) content in Ultisol increased markedly after applying both types of compost, as shown in Fig. 3**D**. Corn stover compost led to a tenfold increase in available P, while rice straw compost increased it by approximately eightfold by the end of the incubation period. This finding corroborates Liu et al. (2018) and Tripathy et al. (2021), who have emphasized the critical role of organic acids in

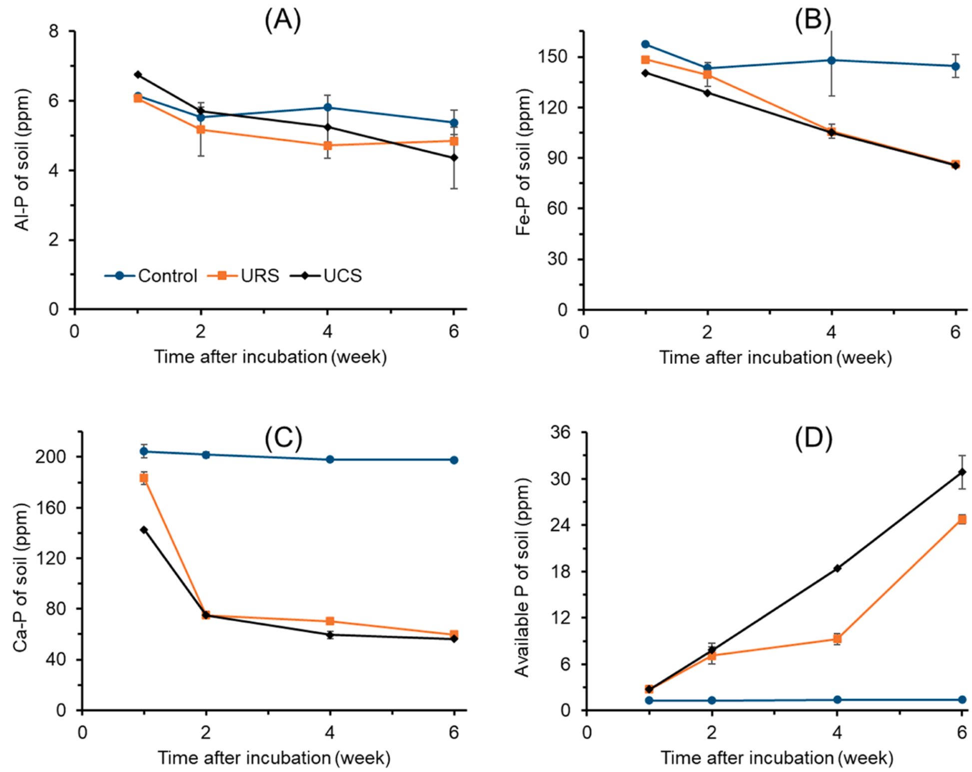


**Fig. 3.** Changes in (A) Al-P complex, (B) Fe-P complex, (C) Ca-P Comple, and (D) Available P in ultisol (U0) and its combination with rice straw (URC, dosed at 20 ta/ha) and corn straw compost (UCS, dosed at 20 ta/ha).

mobilizing insoluble P. The notable increase was mainly due to humic and fulvic acids in the compost facilitating the desorption of P from Al-P, Fe-P, and Ca-P complexes, thereby improving its availability for plant uptake. However, a practical limitation of this study is its short incubation duration and controlled environment, which may not fully capture long-term fluctuations in P-availability under field conditions. Future research should thus examine larger-scale, multi-season trials and consider microbial-driven transformations to gain a comprehensive understanding of how compost continues to influence P-available over time.

### *3.5. Plant response and phosphorus uptake*

The impact of corn stover compost on P uptake in plant tissues and corn kernels is demonstrated in Fig. 4. A direct correlation between compost dosage and P uptake was observed, with the highest absorption

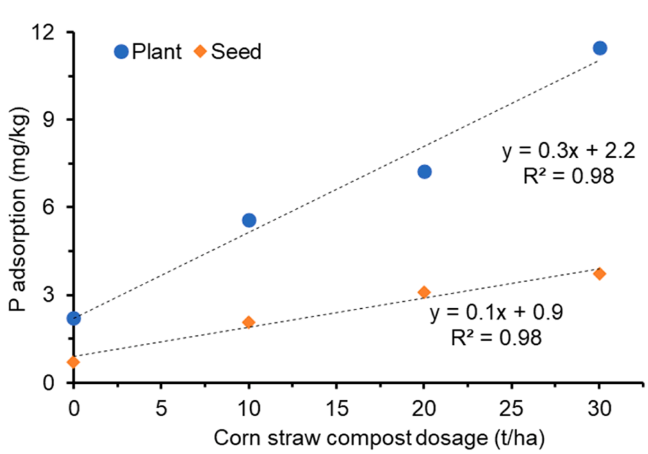


**Fig. 4.** Phosphorous absorption in plants and seeds from corn straw compost.

noted at a compost application rate of 30 t/ha. Interestingly, a linear relationship was identified for P uptake in corn kernels. This suggests that while increased compost doses generally enhance P availability, excessive application may shift the soil's microbial balance, potentially leading to competition for P and other nutrients.

The improved P uptake can be attributed to the presence of humic and fulvic acids in the compost. These compounds are known to enhance P availability by reducing its interactions with metal ions, thus increasing accessibility to plants (Cui et al., 2019). In line with previous findings (Liu et al., 2018), such chelation processes can also promote beneficial microbial activity, creating a more stable soil environment for nutrient uptake. The chelating properties of these acids aid in releasing bound P from soil complexes, making it more accessible for plant absorption. Ultimately, this contributes to enhanced nutrient uptake efficiency and plant growth. Nevertheless, a limitation of this study is the greenhouse-scale duration, which may not fully replicate field conditions over multiple growing seasons. Future research should explore extended field trials to confirm these uptake trends in different cropping systems.

### *3.6. Effect of corn straw compost dosage*

Corn stover compost application significantly impacted corn ear length and diameter (Fig. 5A). Ear length increased linearly with higher compost levels ($R^2 = 0.98$), while ear diameter showed a moderate relationship ($R^2 = 0.61$). These enhancements stem from improved P availability and the positive influence of humic substances on plant physiology. Such linear and moderate correlations are consistent with prior studies (Adusei et al., 2017), suggesting that optimal compost rates may vary based on cultivar-specific nutrient demands.

The enhancements in ear length and diameter were likely due to increased P availability resulting from the compost application, along with the positive impacts of humic substances on plant physiological processes. Studies have demonstrated that humic acids can stimulate

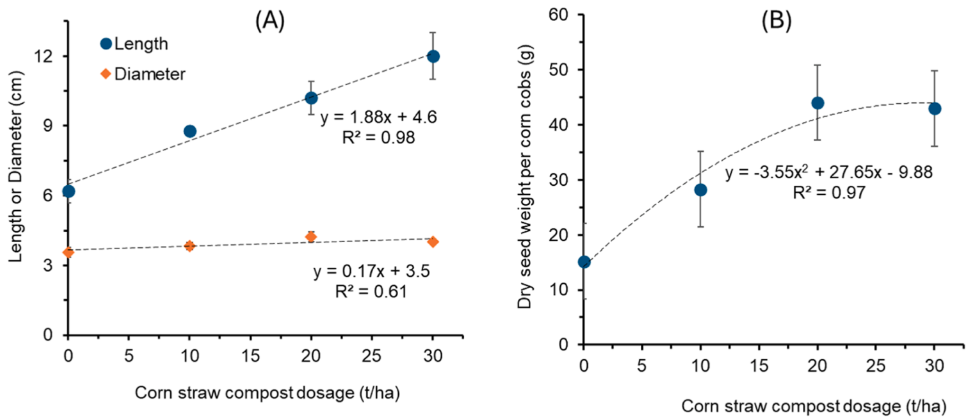


**Fig. 5.** The effect of corn straw compost dosage on (A) length and diameter of corn cobs and (B) on dry seed weight per corn cobs.

root development, enhance nutrient absorption, and support greater biomass production and more robust ear formation. Additionally, the stimulation of beneficial soil microbes by humic substances may improve root efficiency and contribute to these observed morphological gains. These findings are consistent with existing research emphasizing the role of humic substances in improving plant metabolism and growth parameters.

Dry grain weight per ear was significantly impacted by varying levels of corn stover compost application, as depicted in Fig. 5**B**. A quadratic relationship was established, with an $R^2$ value of 0.97, indicating that the compost dosage accounted for almost all the variation in grain weight. The trend suggests that while moderate compost applications led to substantial increases in grain weight, excessive compost did not proportionally increase yield, likely due to nutrient competition or other limiting factors. This aligns with previous findings (Hamidi et al., 2021) that caution against over-application of organic amendments, as imbalances can reduce their net benefits.

The high humic and fulvic acid content in corn stover compost played a crucial role, improving nutrient uptake efficiency and yield. The rise in dry grain weight per ear was associated with enhanced soil fertility resulting from compost application, which improved nutrient availability and fostered optimal plant growth conditions. Moreover, these conditions can favor the growth of beneficial microbes that further aid nutrient cycling. The high concentration of humic and fulvic acids in the corn stover compost played a critical role in boosting nutrient efficiency, thus contributing to higher grain yields. These organic acids not only increased nutrient availability but also enhanced soil structure and microbial activity, creating a more favourable environment for plant growth. Nevertheless, long-term field trials are required to determine whether these yield improvements persist over successive planting seasons and under variable climatic conditions.

## 4. Discussion

This study demonstrates that composts derived from rice straw and corn stover significantly influence P dynamics in Ultisol, with corn stover compost showing a notably stronger capacity to mobilize bound P fractions. The results align with previous research, showing that organic amendments enhance P bioavailability in acidic soils, including Ultisol, Oxisol, and Andisol. For instance, a comparative study reported that compost applications could increase available P by 30–50 % in Ultisol and Oxisol, but the magnitude of improvement often varies based on compost composition (Berek et al., 2018). In this case, the superior performance of corn stover compost likely arises from its higher humic and fulvic acid content, which more effectively chelates metal ions like Al, Fe, and Ca, thus enhancing P solubility.

Consistent with prior research, humic and fulvic acids are essential in improving P availability in acidic soils. These organic acids chelate metal ions, reducing their interaction with P, which prevents P from forming insoluble complexes. Dębicka et al. (2023) and Sofo et al. (2020) both illustrate how humic acids can increase P bioavailability by up to 40 % in acidic soils, primarily by forming stable complexes with metal ions through ligand-exchange reactions. In parallel, our data show that corn stover compost significantly lowered Al-P, Fe-P, and Ca-P levels, thereby boosting available P. This reinforces that humic substances are particularly effective in releasing bound P in these challenging conditions (Urra et al., 2019).

Furthermore, this study confirms the effectiveness of organic amendments in supporting crop productivity in nutrient-poor soils like Ultisol. Enhanced P availability due to corn stover compost corresponded to improved agronomic traits, including greater ear length, diameter, and grain yield. These improvements illustrate how enhanced soil fertility and P uptake can translate into tangible yield gains. Similar benefits have been documented, with compost reducing reliance on chemical fertilizers, cutting costs, and decreasing environmental pollution from fertilizer runoff (Paramisparam et al., 2021). Additionally, compost improves soil structure and water retention, vital for crop resilience in tropical climates (Kim et al., 2022).

Nevertheless, a key limitation of this study is that it focused on P availability, organic amendments are also known to contribute to soil health by adding organic matter and potentially stimulating beneficial soil microbes, though direct microbial assessments were not performed here. As a sustainable agricultural practice, composting contributes to carbon sequestration and supports circular economy principles by converting agricultural waste into valuable soil amendments (Paramisparam et al., 2021). Using locally available materials, such as rice straw and corn stover, composting serves as a sustainable waste management approach that bolsters soil biodiversity, improves nutrient cycling, and supports long-term agricultural productivity.

Optimal compost application rates are crucial. Moderate applications of corn stover compost increased P availability and yield, yet over-application did not yield proportional benefits, suggesting that there is a threshold beyond which additional compost may induce resource competition or nutrient imbalances. This finding aligns with research suggesting that optimal compost application rates vary by soil and crop type, with overuse leading to diminishing returns and potential imbalances in soil nutrient availability (Hamidi et al., 2021).

Long-term effects of compost application on P dynamics in Ultisol are another critical consideration. Studies suggest that regular compost application can result in sustained improvements in soil fertility over time, with some reporting a 50 % increase in available P after five years of consistent application (Berek et al., 2018). However, definitive data on the long-term effects on soil microbial communities and soil structure remain under-researched, necessitating further study. Research is needed to determine optimal compost application rates and frequencies that maximize P availability while ensuring soil health and structure stability over time (Duşa, 2023; Hamidi et al., 2021).

This study adds to the evidence that organic amendments are viable, sustainable soil management practices. By alleviating P deficiencies in Ultisols, compost boosts crop productivity, essential for food security in tropical regions. Notably, corn stover compost's humic and fulvic acids are key to unlocking recalcitrant P fractions, demonstrating that compost choice can be tailored to soil conditions for maximum efficacy. Past studies support the critical role of humic and fulvic acids in enhancing P uptake, thus fostering robust plant growth (Sofo et al., 2020; Urra et al., 2019).

Future research should focus on refining organic amendment practices to address specific soil management challenges in tropical environments. For instance, exploring the interactions between compost and soil microbial communities may offer insights into how compost applications affect nutrient cycling over the long term. Studies examining the impact of compost on soil structure, erosion resistance, and carbon sequestration will also be essential to understand the full benefits provided by organic amendments (Kim et al., 2022). Additionally, assessing the comparative effectiveness of different types of organic amendments, such as compost versus manure, could provide a clearer understanding of optimal applications for specific soils (Bertici et al., 2022).

Overall, this study reinforces the value of compost in promoting sustainable agriculture, particularly in resource-limited settings where reliance on synthetic fertilizer maybe financially or environmentally unsustainable. Given the wide availability of agricultural residues like rice straw and corn stover, targeted composting provides an accessible strategy for enhancing soil P availability, nurturing long-term agricultural productivity and fostering environmental stewardship in tropical soils. Nonetheless, multi-season field investigations are needed to validate whether the short-term benefits identified here translate into durable gains across diverse cropping systems and climatic conditions.

## 5. Conclusion

This study illustrates that composts derived from rice straw and corn stover significantly enhance P availability in Ultisol soils, with corn stover compost demonstrating greater effectiveness in reducing Al-P, Fe-P, and Ca-P complexes (up to 67 %) and raising available P levels by nearly 10-fold. These changes translated into notable improvements in corn yield, including increases in ear length, diameter, and grain weight. The elevated humic and fulvic acid content in corn stover compost facilitated metal ion chelation and thus more effective P release into plant-accessible forms. Additionally, these findings suggest that compost derived from locally available agricultural residues offers a cost-effective and sustainable alternative to chemical fertilizers, benefiting soil fertility and crop productivity. Nevertheless, the current findings are based on short-term greenhouse and incubation trials, which may not fully capture longer-term field-level variations in tropical soils. Future studies should therefore further assess multi-season impacts on P dynamics and identify optimal compost application rates for long-term soil health and yield in tropical agriculture. Such an approach would provide deeper insights into microbial community shifts, soil structural changes, and economic feasibility, ensuring a holistic understanding of compost's role in sustainable soil management.

## CRediT authorship contribution statement

**Muhammad Roil Bilad:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Kasifah Kasifah:** Writing – original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sumbangan Baja:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to enhance the clarity of the writing. After using the ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

## References

Adusei, G., Gaiser, T., Boukar, O., Fatokun, C., 2017. Growth and yield responses of cowpea genotypes to soluble and rock p fertilizers on acid, highly weathered soil from humid tropical west africa. Int. J. Biol. Chem. Sci. 10 (4), 1493. https://doi.org/10.4314/ijbcs.v10i4.3.

Berek, A., Hue, N., Radovich, T., Ahmad, A., 2018. Biochars improve nutrient phytoavailability of hawai'i's highly weathered soils. Agronomy 8 (10), 203. https://doi.org/10.3390/agronomy8100203.

Bertici, R., Dicu, D., Herbei, M., Sala, F., 2022. The potential of pig sludge fertilizer for some pasture agricultural lands' improvement: case study in timiş county, romania. Agronomy 12 (3), 701. https://doi.org/10.3390/agronomy12030701.

Chen, Shuotong, Ding, Yuanjun, Xia, Xin, Feng, Xiao, Liu, Xiaoyu, Zheng, Jufeng, Drosos, Marios, Cheng, Kun, Bian, Rongjun, Zhang, Xuhui, Li, Lianqing, Pan, Genxing, 2021a. Amendment of straw biochar increased molecular diversity and enhanced preservation of plant derived organic matter in extracted fractions of a rice paddy. J. Environ. Manag. 285, 112104. https://doi.org/10.1016/j.jenvman.2021.112104.

Chen, Yanrong, Chen, Yaoning, Li, Yuanping, Liu, Yihuan, Li, Hui, Jiang, Hongjuan, Luo, Xinli, Tang, Ping, Chen, Li, Yan, Haoqin, 2021b. Evolution of humic substances and the forms of heavy metals during Co-composting of rice straw and sediment with the aid of Fenton-like process. Bioresour. Technol. 333 (April), 125170. https://doi.org/10.1016/j.biortech.2021.125170.

Chulo, Fikeremareyam, Laekemariam, Fanuel, Kiflu, Alemayehu, 2021. Changes in soil phosphorus pools and chemical properties under liming in nitisols of Farawocha, South Ethiopia. Appl. Environ. Soil Sci. 2021. https://doi.org/10.1155/2021/5518545.

Cui, Hu, Ou, Yang, Wang, Lixia, Yan, Baixing, Han, Lu, Li, Yingxin, 2019. Change in the distribution of phosphorus fractions in aggregates under different land uses: a case in Sanjiang Plain, Northeast China. Int. J. Environ. Res. Public Health 16 (2), 1–14. https://doi.org/10.3390/ijerph16020212.

Dębicka, M., Jamroz, E., Bekier, J., Ćwieląg-Piasecka, I., Kocowicz, A., 2023. The influence of municipal solid waste compost on the tranformations of phosphorus forms in soil. Agronomy 13 (5), 1234. https://doi.org/10.3390/agronomy13051234.

Duşa, E., 2023. Soil chemical properties and microbial behavior under short-term organic and mineral fertilization within different crops. Agronomy 13 (11), 2837. https://doi.org/10.3390/agronomy13112837.

Ekpo, U., Ross, A., Camargo-Valero, M., Fletcher, L., 2016. Influence of ph on hydrothermal treatment of swine manure: impact on extraction of nitrogen and phosphorus in process water. Bioresour. Technol. 214, 637–644. https://doi.org/10.1016/j.biortech.2016.05.012.

Graaf, I., Gleeson, T., Beek, L., Sutanudjaja, E., Bierkens, M., 2019. Environmental flow limits to global groundwater pumping. Nature 574 (7776), 90–94. https://doi.org/10.1038/s41586-019-1594-4.

Gupta, Arbind Kumar, Patra, Prashanta Kumar, Tripathi, Luxmi Kant, 2020. Distribution and classification of phosphorus fractions and their relationship with soil properties in ultisols of Meghalaya. J. Indian Soc. Soil Sci. 68 (4), 400–407. https://doi.org/10.5958/0974-0228.2020.00030.4.

Hamidi, N., Ahmed, O., Omar, L., Ch'ng, H., 2021. Soil nitrogen sorption using charcoal and wood ash. Agronomy 11 (9), 1801. https://doi.org/10.3390/agronomy11091801.

Hasbullah, Nur Aainaa, Ahmed, Osumanu Haruna, Ab Majid, Nik Muhamad, 2020. Effects of amending phosphatic fertilizers with clinoptilolite zeolite on phosphorus

availability and its fractionation in an acid soil. Appl. Sci. 10 (9). https://doi.org/10.3390/app10093162.
Hiradate, Syuntaro, Yonezawa, Takuya, Takesako, Hiroshi, 2007. Fine fractionation and purification of the fulvic acid fraction using adsorption and precipitation procedures. Soil Sci. Plant Nutr. 53 (4), 413–419. https://doi.org/10.1111/j.1747-0765.2007.00159.x.
Kim, Y., Cho, Y., Lee, J., Seo, H., Kim, B., Lee, D., Kim, K., 2022. Short-term responses of soil organic carbon pool and crop performance to different fertilizer applications. Agronomy 12 (5), 1106. https://doi.org/10.3390/agronomy12051106.
Liu, Shi Lei, Qi, Wang, Bing, Qian Fan, Zhang, Qiang, Chen, Qing, 2018. Effects of chelating agents on phosphorus release from different phosphorus sources. J. Agro-Environ. Sci. 37 (9), 1895–1902. https://doi.org/10.11654/jaes.2017-1673.
Lukmansyah, Andri, Niswati, Ainin, Buchari, Henrie, Salam, Abdul Kadir, 2020. Pengaruh Asam humat Dan Pemupukan P terhadap respirasi tanah pada pertanaman jagung di tanah ultisols. J. Agrotek Trop. 8 (3), 527. https://doi.org/10.23960/jat.v8i3.4529.
Montalvo, D., Vanderschueren, R., Fritzsche, A., Smolders, E., 2018. Efficient removal of arsenate from oxic contaminated water by colloidal humic acid-coated goethite: batch and column experiments. J. Clean. Prod. 189, 510–518. https://doi.org/10.1016/j.jclepro.2018.04.055.
Ojo, Abigail O., Adetunji, Michael T., Adejuyigbe, Christopher O., Fademi, Ibukun O., 2018. Response of three soils in the derived Savanna zone of Southwestern Nigeria to combined application of organic and inorganic fertilizer as affecting phosphorus fractions. Eurasia J. Soil Sci. 7 (2), 187–194. https://doi.org/10.18393/ejss.393289.
Paramisparam, P., Ahmed, O., Omar, L., Ch'ng, H., Maru, A., Johan, P., 2021. Amending potassic fertilizer with charcoal and sago (Metroxylon sagu) bark ash to improve potassium availability in a tropical acid soil. Agronomy 11 (11), 2222. https://doi.org/10.3390/agronomy11112222.
Pasang, Yafet Hendri, Jayadi, Muh, Neswati, Risma, 2019. Peningkatan Unsur Hara Fospor Tanah Ultisol Melalui Pemberian Pupuk Kandang, Kompos Dan Pelet. J. Ecosolum 8 (2), 86. https://doi.org/10.20956/ecosolum.v8i2.7872.
Pierzynski, G.M. 2009. Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters. Southern Cooperative Series Bulletin.
Rahmi, Eka, Suwardi, Suwardi, Sumawinata, Basuki, 2018. Characterization of humic substance extracted from andisols, spodosols, peat, and lignite. SAINS TANAH - J. Soil Sci. Agroclimatol. 15 (1), 35. https://doi.org/10.15608/stjssa.v15i1.21622.
Reyes-Bozo, L., Godoy-Faúndez, A., Herrera-Urbina, R., Higueras, P., Salazar, J., Valdés-González, H., Antízar-Ladislao, B., 2014. Greening chilean copper mining operations through industrial ecology strategies. J. Clean. Prod. 84, 671–679. https://doi.org/10.1016/j.jclepro.2014.03.088.
Simpson, R., Oberson, A., Culvenor, R., Ryan, M., Veneklaas, E., Lambers, H., Richardson, A., 2011. Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant Soil 349 (1-2), 89–120. https://doi.org/10.1007/s11104-011-0880-1.
Sofo, A., Mininni, A., Ricciuti, P., 2020. Soil macrofauna: a key factor for increasing soil fertility and promoting sustainable soil use in fruit orchard agrosystems. Agronomy 10 (4), 456. https://doi.org/10.3390/agronomy10040456.
Sootahar, M., Zeng, X., Su, S., Wang, Y., Bai, L., Yang, Z., Zhang, X., 2019. The effect of fulvic acids derived from different materials on changing properties of albic black soil in the northeast plain of china. Molecules 24 (8), 1535. https://doi.org/10.3390/molecules24081535.
S.ALansari, A., M.Yassin, M., W.Seheib, M., 2018. Role of organic acids on phosphorus fractions in silty clay loam soil. Al-Qadisiyah J. Agric. Sci. 8 (2), 12–21. https://doi.org/10.33794/qjas.2018.162634.
Stevenson, F.J. 1994. Humus Chemistry, Genesis, Composition, Reactions. Second edition. New York: John Wiley & Sons, Inc.
Sukitprapanon, Tanabhat Sakorn, Jantamenchai, Metawee, Tulaphitak, Duangsamorn, Prakongkep, Nattaporn, Gilkes, Robert John, Vityakon, Patma, 2021a. Influence of application of organic residues of different biochemical quality on phosphorus fractions in a tropical sandy soil. Agronomy 11 (2). https://doi.org/10.3390/agronomy11020248.
Sukitprapanon, Tanabhat Sakorn, Jantamenchai, Metawee, Tulaphitak, Duangsamorn, Prakongkep, Nattaporn, Gilkes, Robert John, Vityakon, Patma, 2021b. Influence of application of organic residues of different biochemical quality on phosphorus fractions in a tropical sandy soil. Agronomy 11 (2). https://doi.org/10.3390/agronomy11020248.
Tripathy, S., Meena, S.L., Babu, S., Das, T.K., Dhar, S., 2021. Phosphorus pools under integrated phosphorus management of upland direct-seeded rice (Oryza sativa) in North-eastern hill region of India. Indian J. Agron. 66 (4), 495–497.
Urra, J., Alkorta, I., Garbisu, C., 2019. Potential benefits and risks for soil health derived from the use of organic amendments in agriculture. Agronomy 9 (9), 542. https://doi.org/10.3390/agronomy9090542.
Wu, Huiqiao, Kida, Morimaru, Domoto, Akiko, Hara, Masayuki, Ashida, Hitoshi, Suzuki, Takeshi, Fujitake, Nobuhide, 2019. The effects of fertilization treatments and cropping systems on long-term dynamics and spectroscopic characteristics of dissolved organic matter in paddy soil. Soil Sci. Plant Nutr. 65 (6), 557–565. https://doi.org/10.1080/00380768.2019.1689794.
Xu, W., Liu, L., He, T., Cao, M., Sha, L., Hu, Y., Li, J., 2016. Soil properties drive a negative correlation between species diversity and genetic diversity in a tropical seasonal rainforest. Sci. Rep. 6 (1). https://doi.org/10.1038/srep20652.
Yang, Xiaoyan, Kong, Yuhua, Guo, Erhui, Chen, Xiangwei, Li, Limei, 2022. Organic acid regulation of inorganic phosphorus release from mollisols with different organic matter contents. Soil Use Manag. 38 (1), 576–583. https://doi.org/10.1111/sum.12710.
Yao, Q., Li, Z., Song, Y., Wright, S., Guo, X., Tringe, S., Pan, C., 2018. Community proteogenomics reveals the systemic impact of phosphorus availability on microbial functions in tropical soil. Nat. Ecol. Evol. 2 (3), 499–509. https://doi.org/10.1038/s41559-017-0463-5.