International Journal of Agricultural Technology 2026 Vol. 22(1):475-488
DOI: https://doi.org/10.63369/ijat.2026.22.1.475-488
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

Increasing phosphorus uptake and sweet corn yield through *Azolla pinnata* compost and lime application in Ultisols

Setyowati, N.[1*], Muktamar, Z.[2], Sahara, W.[2] and Hasanudin, H.[2]

[1]Department of Crop Production, University of Bengkulu, Bengkulu, Indonesia; [2]Department of Soil Science, University of Bengkulu, Bengkulu, Indonesia.

Setyowati, N., Muktamar, Z., Sahara, W. and Hasanudin, H. (2026). Increasing phosphorus uptake and sweet corn yield through *Azolla pinnata* compost and lime application in Ultisols. International Journal of Agricultural Technology 22(1):475-488.

Abstract Azolla compost significantly increased total soil organic carbon (TSOC) by 27% and soil pH by 20.6% at 15 tons/ha compared to unfertilized soil, but comparable with 10 ton/ha. Phosphorus uptake by sweet corn was more than doubled with the application of Azolla compost at 10 tons/ha as compared to unfertilized soil, accompanied by increases in shoot dry weight and unhusked ear weight by 1.23 times and 81.9%, respectively. In general, the application of Azolla compost at a rate of 10 ton/ha is sufficient to increase productivity of sweet corn in Ultisols. While calcium carbonate application significantly improved soil pH and P tissue concentration, it had no effect on TSOC, phosphorus uptake, shoot weight, or unhusked ear weight. These findings provide valuable insights for optimizing sweet corn fertilization in Ultisols.

Keywords: Soil organic carbon, Soil pH improvement, Phosphorus uptake efficiency, Sweet corn productivity, Sustainable soil amendment

Intoduction

Sweet corn *(Zea mays* var. *saccharata*) plays an important role in increasing global food security. It has high nutritional content, including essential vitamins, minerals, and dietary fiber, becoming as important food in many regions. Sweet corn grows well to diverse climate, contributing to widespread adoption by farmers (Sidahmed *et al*., 2024). Likewise, its ability to grow in marginal lands makes it a potential crop for ensuring food availability (Sidahmed *et al*., 2025. Sweet corn significantly strengthens food security and contribute to sustainable farming practices.

Cultivating sweet corn in Ultisols faces challenges due to their high acidity and low P availability. High aluminum saturation in the soils can inhibit root and shoot growth and reduce nutrient uptake by plants (Rahman *et al*., 2024; Shetty *et al*., 2021). Moreover, phosphorous, as an essential nutrient for crop growth and development is frequently not available due metal fixation. High content of

[*]**Corresponding Author:** Setyowati, N.; **Email:** nsetyowati@unib.ac.id

Al and Fe reduces P availability, resulting in high sorption capacity in acid soils (Yi *et al*., 2023; Omenda *et al*., 2021; Ifansyah, 2013). Cultivating sweet corn in Ultisols often employ soil management strategies such liming neutralizes acidity and the application of organic fertilizer to improve soil properties.

Calcium carbonate is a commonly used method for reducing soil acidity. It works by neutralizing acidity through its reaction with acidic cations like aluminum (Al) and iron (Fe), thereby decreasing proton production and raising the soil pH to a range more suitable for crop growth and development. By reducing the saturation of Al and Fe in the soil, it also effectively lessens the risks associated with aluminum toxicity. Study by Herrera and Perez (2020) demonstrated that applying lime up to a rate of 4.5 ton/ha resulted in a linear increase in soil pH and a reduction in exchangeable acidity. Additionally, the availability of phosphorus in the soil showed a significant improvement.

Adding organic matter is crucial for enhancing nutrient availability and creating a favorable rhizosphere for sweet corn growth. Azolla (*Azolla pinnata*) compost is widely used for this purpose. *A. pinnata* itself contains 11.61–13.12% fat, 27.15–27.17% protein, 9.64–12.66% fiber, 2.55–3.95% nitrogen, 0.35–0.85% phosphorus, and 1.80–3.90% (Said *et al*., 2023; Sambodo *et al*., 2014). Its compost, on the other hand, has 34.78–35.83% organic carbon, 3.10–3.17% total nitrogen, 0.95–1.10% phosphorus, 1.57–1.81% potassium, a C/N ratio of 11.21–11.30, and a pH ranging from 7.12 to 7.30 (Seleiman *et al*., 2022).

The use of Azolla compost significantly improves soil chemical properties. According to Rashid *et al*. (2024), Azolla compost increases total organic-N, total-N, available-P, exchangeable K, and soil pH. Its application also increases exchangeable Ca, Mg, and cation exchange capacity (CEC). Additionally, it promotes microbial activity, as evidenced by higher emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) (Jumadi *et al*., 2014). Over time, Azolla compost reduces soil acidity (Swami and Singh, 2019), particularly when combined with lime, thereby fostering a more favorable environment for plant growth and enhancing soil fertility. The study aimed to investigate the P uptake and sweet corn yield following the application of Azolla compost and calcium carbonate in Ultisols

Materials and methods

Soil sampling and media preparation

The experiment was carried out in the greenhouse of the Faculty of Agriculture, University of Bengkulu, Indonesia. Ultisols were used in this study, collected from the Faculty of Agriculture Experiment Station in Medan Baru

Village, Bengkulu City. Soil samples were compositely collected from five spots at a depth of 0–20 cm, air-dried for two days, ground, and sieved through a 2 mm screen. A portion of the sample was further sieved through a 0.5 mm screen to determine the initial characteristics of the soil. The initial characteristics of the soil were 2.09% organic-C, 0.20% total N, 5.24 mg/kg available P, 54.6 mg/kg available K, 3.73 cmol/kg exchangeable Al, and pH of 4.72.

Experimental design and treatments

The experiment employed a Completely Randomized Design (CRD) with two factors. The first factor was Azolla compost applied at rates of 0, 5, 10, and 15 tons/ha, while the second factor was agricultural lime ($CaCO_3$) applied at rates of 0, 3.41, and 6.82 tons/ha. The lime application rates were determined based on the concentration of exchangeable aluminum, which initially measured 3.73 cmol/kg in the soil. Each treatment combination was repeated three times, with each experimental unit replicated twice.

Azolla compost preparation

Fresh Azolla was chopped into 2–3 cm pieces and air-dried for three days. The dried Azolla was placed into 10 kg plastic composting bags. Each bag received 200 ml of an EM-4 solution and 100 g of sugar, which were thoroughly mixed to achieve uniform distribution. The mixture was incubated for four weeks, with weekly turning to facilitate aeration. Upon completion of the incubation period, the compost was prepared for application. The compost contained 2.57% N, 0.34% P, and 0.03% K.

Cultivation procedure

The growing medium was prepared using air-dried Ultisols. A 10 kg soil sample was placed into a polybag and treated with the specified rates of Azolla compost and agricultural lime. The treated soil was incubated for one week to facilitate chemical reactions. Following the incubation period, two sweet corn seeds were sown into holes at a depth of 2 cm. The holes were subsequently covered with soil to ensure proper seed placement and germination conditions.

Thinning was conducted two weeks after planting, retaining the healthier sweet corn plant in each polybag. Weed management was performed manually by removing weeds present in the growing media. Sweet corn was harvested 90 days after planting, with maturity determined by several indicators: yellowing of the leaves, yellowish coloration of the ears, browning of the ear silks, firmness and fullness of the ears upon gentle pressure, and the exudation of a milky white solution from the kernels. The observed variables included plant height, shoot fresh weight, shoot dry weight, and unhusked ear weight. Additionally, phosphorus concentration in plant tissues was assessed using the wet extraction method as outlined by Balai Penelitian Tanah (2009). Phosphorous uptake by plant was calculated using P concentration and shoot dry weight. Following harvest, soil samples were collected from each polybag, air-dried for two days, and sieved through a 0.5 mm screen. The samples were analyzed for Total Soil Organic Carbon (TSOC) using the Walkley and Black method, and pH was measured using a pH meter with a soil-to-distilled water ratio of 1:2.5.

Data analysis

Data were anlyzed using ANOVA at probability level of 5% on SAS for Academic. Mean comparison was calculated using DMRT at probability level of 5%.

Results

The study indicated that Azolla compost significantly influenced TSOC, soil pH, P tissue concentration, P uptake, plant height, stem diameter, shoot fresh weight per plant, shoot dry weight per plant and unhusked ear weight ($p<0.05$). Additionally, lime ($CaCO_3$) substantially affected soil pH, P tissue concentration, and plant height but there were no significant differences on organic-C, P uptake, shoot fresh weight, shoot dry weight and unhusked ear weight. The combination effects of both factors were not observed in the study (Table 1).

Table 1. Analysis of variances for selected soil and plant variables

Variables	**Probability F < 0.05**		
	Azolla Compost	Lime	Interaction
Organic-C	0.019	0.341	0.676
pH	0.003	< 0.0001	0.170
P tissue concentration	0.001	0.002	0.364
P uptake	0.033	0.323	0.743
Plant height	0.001	0.001	0.266
Shoot fresh weight	0.004	0.123	0.776
Shoot dry weight	0.037	0.399	0.883
Unhusked ear weight	0.004	0.117	0.752

Effect of Azolla compost on selected soil properties and sweet corn performance

The application of Azolla compost notably enhanced TSOC, as presented in Figure 1a. TSOC remained comparable up to an application rate of 10 tons/ha of Azolla compost but showed a significant increase at 15 tons/ha. When the soil was fertilized with 15 tons/ha of Azolla compost, TSOC rose by nearly 27% compared to unfertilized soil. The increase in TSOC was accompanied by a rise in soil pH (Figure 1b). The concentration of phosphorus (P) in sweet corn tissues steadily increased with the application of Azolla compost (Figure 1c) and the increase in P concentration in sweet corn tissues was accompanied by an increase in P uptake (Figure 1d).

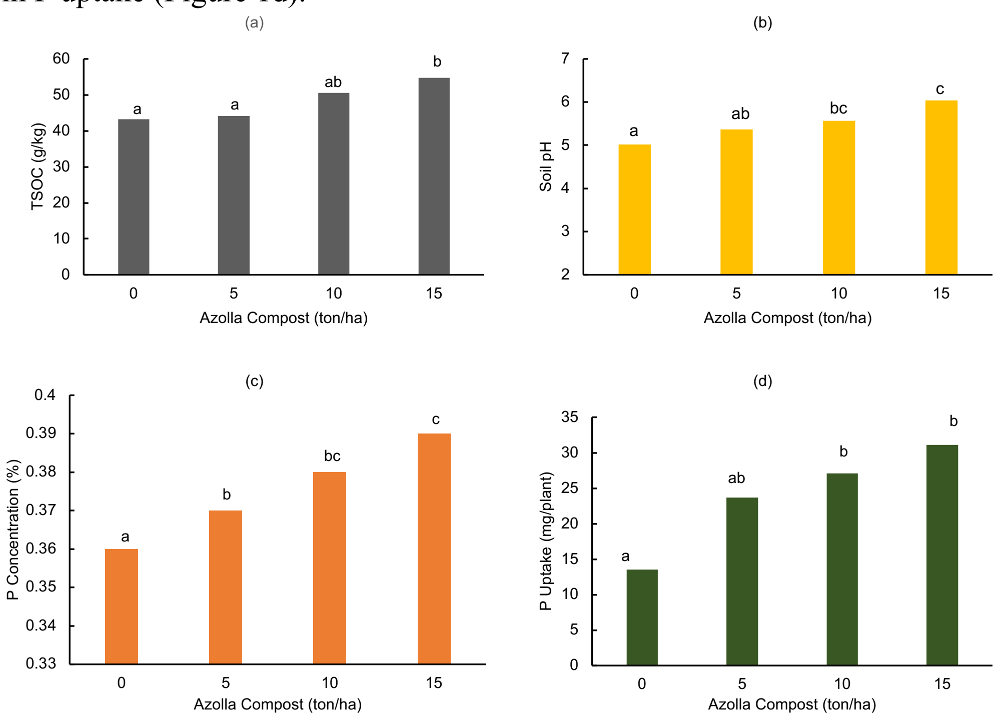

Figure 1. Effect of Azolla compost on Total Soil Organic Carbon (TSOC) (a), soil pH (b), P concentration (c) and P uptake by plant (d)

The application of Azolla compost significantly enhanced plant height, with a 16.2% increase at a rate of 5 ton/ha compared to the control (Figure 2a). However, plant height at 5 ton/ha did not differ from 10 dan 15 ton/ha. A significant increase was also observed in shoot fresh and dry weight (Figure 2b and c). Shoot fresh weight increased from 35.9 g/plant in the control to 77.3 g/plant in the rate of 10 ton/ha, which was comparable to the weight observed at

15 ton/ha. A similar trend was distinguished in shoot dry weight. These results contributed the increase in the yield of sweet corn as indicated by the weight of unhusked ear (Figure 2d).

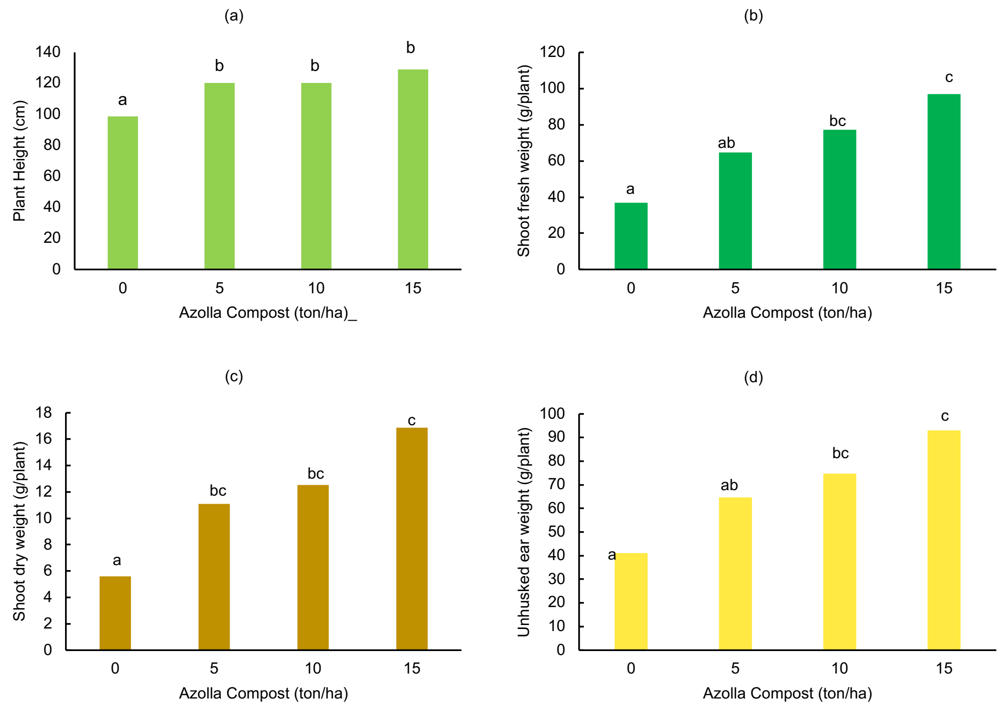

Figure 2. Effect of Azolla compost on plant height (a), shoot fresh weight (b), shoot dry weight (c) and unhusked ear weight (d)

Effect of liming on selected soil properties and sweet corn performance

The study resulted no effect of calcium carbonate on TSOC but a significant increase in soil pH. TSOC ranged from 46.2 to 51.2 g/kg with lime application rate between 0-6.82 ton/ha (Figure 3a). Applying calcium carbonate resulted in a steady increase in soil pH, as illustrated in Figure 3b. The study also found that P uptake by sweet corn remained unaffected by different rates of calcium carbonate application and the phosphorus uptake varied between 20.1 and 27.7 mg per plant (Figure 3c and 3d).

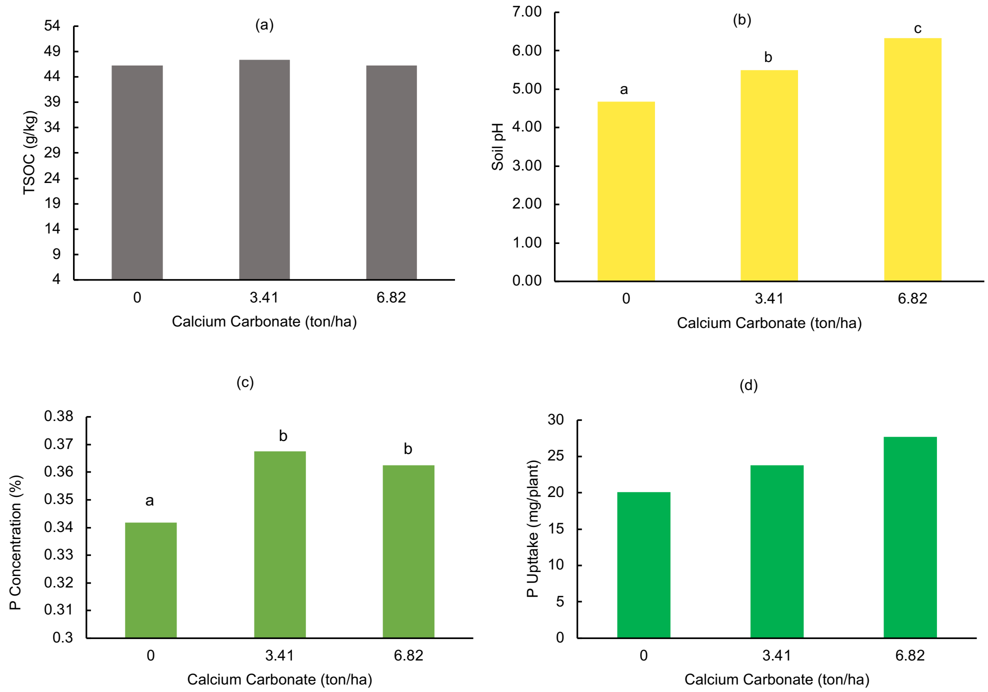

Figure 3. Effect of Calcium Carbonate on Total Soil Organic Carbon (TSOC) (a), soil pH (b), P tissue concentration (c) and uptake by sweet corn (d)

The study resulted that applying calcium carbonat at different rate did not influence shoot weight and uhusked ear. Shoot fresh weight ranged from 53.0 to 77.8 g/plant, shoot dry weight from 9.1 to 13.2 g/plant and unhusked ear from 54.7 to 76.3 g/plant (Figure 4 b, 4c and 4d). However, plant height significantly increased with higher rate of lime, showing a 29% increased at a rate of 6.82 ton/ha compared to control.

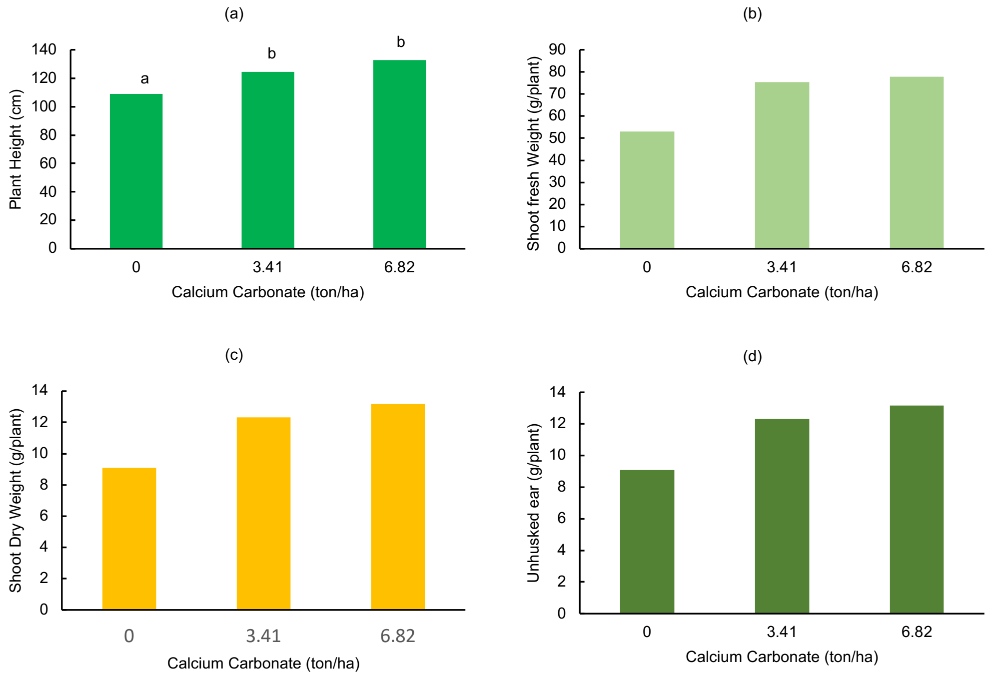

Figure 4. Effect of Calcium Carbonate on plant height (a), shoot fresh weight (b), shoot dry weight (c), unhusked ear (d)

Disscussion

Organic matter from compost will eventually contribute carbon to the soil. Previous studies have demonstrated that Azolla compost enhances organic carbon in the soil (Bharali *et al*., 2021; Rashid *et al*., 2024; Novair *et al*., 2020). The increase in TSOC was accompanied by a rise in soil pH. During decomposition, Azolla compost produces stable organic acids, such as humic and fulvic acids, which are rich in functional groups, such as carboxyl and phenolic, capable of forming covalent bonds with metals to create organo-metallic complexes (Spark, 2003). The soil in this study, classified as Ultisols, contains high exchangeable aluminum (3.73 cmol/kg). The formation of aluminum-organic complexes hinders aluminum hydrolysis, thereby reducing the generation of hydrogen ions in the system and resulting in an increase in pH. Previous studies confirmed that applying organic matter to acidic soil increases soil pH pH (Muktamar *et al*. 2016; Muktamar *et al*., 2018; Muktamar *et al*., 2022; Chen *et al*. 2022; Zhang *et al*., 2023).

The concentration of phosphorus (P) in sweet corn tissues steadily increased with the application of Azolla compost. The increase in P concentration in sweet corn tissues was accompanied by an increase in P uptake. P uptake was more than doubled, rising from 13.5 g/plant in the control to 27.1 g/plant at a compost application rate of 10 tons/ha, which was not significantly different from the uptake at 15 tons/ha. This result suggested that applying Azolla compost at a rate of 10 tons/ha is sufficient to enhance P absorption in sweet corn. P concentration rose by 8.7% when the soil was fertilized with 15 tons/ha of Azolla compost compared to the control. During decomposition, Azolla compost releases P into the soil, making it readily available for plant uptake. Additionally, P bound in aluminum and iron phosphates, which are typically stable in acidic soils, is released into the soil solution through the exchange of phosphate ions by the functional groups in humic and fulvic acids. Previous studies have reported that the addition of humic acid to acidic soils increases the availability of phosphorus (P) in the soil solution by reducing the rate of P fixation (Maluf *et al*., 2018; Jing *et al*., 2023). This released P is also readily accessible to plants.

Improvement of soil condition and the availability of nutrient support plant growth. In this study, more favorable soil pH and the availability of nutrient has increased P uptake by sweet corn, which in turn increase the growth and yield. The application of Azolla compost significantly enhanced plant height, with a 16.2% increase at a rate of 5 ton/ha compared to the control. However, plant height at 5 ton/ha did not differ from 10 dan 15 ton/ha. A significant increase was also observed in shoot fresh and dry weight. Shoot fresh weight increased from 35.9 g/plant in the control to 77.3 g/plant in the rate of 10 ton/ha, which was comparable to the weight observed at 15 ton/ha. A similar trend was distinguished in shoot dry weight. These results contributed the increase in the yield of sweet corn as indicated by the weight of unhusked ear.

These findings are associated with the improvement of soil properties and nutrient availability, particularly phosphorus (P) absorption, as shown in Figure 1d. According to Uchida (2000), phosphorus plays a essential role in root development, flower initiation, and seed formation, in addition to its primary function in energy transfer during photosynthesis and respiration. An increase in P uptake proportionally enhances shoot dry weight, husked ear weight, and unhusked ear weight of sweet corn, as reported by Fahrurrozi *et al*. (2019). Similarly, previous study has demonstrated that Azolla compost significantly improves plant height, leaf number, ear count per plant, ear length, and unhusked ear weight (Maruapey *et al*., 2022). Overall, applying Azolla compost at a rate of 10 tons/ha is sufficient to boost sweet corn growth and yield.

The study resulted no effect of calcium carbonate on TSOC but a significant increase in soil pH. TSOC ranged from 46.2 to 51.2 g/kg with lime application rate between 0-6.82 ton/ha. Previous studies reported inconsistent effect of lime on content of soil organic-C. Moore *et al*. (2012) observed a decrease in organic-C in forest soils with increasing doses of dolomitic lime.

Conversely, Sramek *et al*. (2012) confirmed that lime application increased soil organic-C. However, several researchers reported no significant effect of lime on TSOC (Mijangos *et al*., 2010; Costa, 2012; Hwang and Sang, 2006; Grieve *et al*., 2005). According to Paradelo *et al*. (2015), an increase in soil organic-C might result from the improvement of plant productivity, which returns more organic matter to the soil. On the other hand, improvement in soil pH due to liming stimulates microbial activity, accelarating organic matter decomposition, in turn reducing soil organic-C.

Applying calcium carbonate resulted in a steady increase in soil pH. Compared to control, soil pH rose by 17% and 34% when lime was applied at rates of 3.41 and 6.82 tons/ha, respectively. This is increasingly attributed to release of hydroxyl ions into the soil solution as lime dissolves. The Ultisols used in this study had a low initial pH (4.74) and high exchangeable aluminum (3.73 cmol/kg). The presence of hydroxyl ions reacts with Al^{3+} in the soil solution, forming insoluble $Al(OH)_3$, which reduces aluminum hydrolysis. Additionally, hydrogen ion neutralization further contributes to the rise in soil pH. Previous studies have confirmed that liming significantly increases soil pH and exchangeable calcium while reducing exchangeable aluminum (Mahmud and Chong, 2022; Olego *et al*., 2021; Ejigu *et al*., 2023; Dinkecha and Tsegaye, 2017). The rise in soil pH was followed by an increase in phosphorus tissues concentration with higher rates of calcium carbonate application. This might be associated with release of P previously fixed by Al and Fe in the soil. Studi by Alemu *et al*. (2022) confirmed that available P increased with the application of $CaCO_3$. However, the study also found that P uptake by sweet corn remained unaffected by different rates of calcium carbonate application. Phosphorus uptake varied between 20.1 and 27.7 mg per plant

The study also resulted that applying calcium carbonat at different rate did not influence shoot weight and uhusked ear. Shoot fresh weight ranged from 53.0 to 77.8 g/plant, shoot dry weight from 9.1 to 13.2 g/plant and unhusked ear from 54.7 to 76.3 g/plant. However, plant height significantly increased with higher rate of lime, showing a 29% increase at a rate of 6.82 ton/ha compared to control. A study by Casumlong and Galgo (2020) reported similar result where application of calcium carbonate did not affect leaf area index, shoot weigh and ear weight.

In summary, application of Azolla compost up to the rate of 10 ton/ha substantially increased total soil organic carbon and soil pH, leading to enhanced P uptake, as well as improved growth and yield of sweet corn, as reflected in increased plant height, shoot fresh and dry weight as well as uhusked ear weight. In contrast, calcium carbonate application at 6.82 tons/ha raised soil pH by 34% compared to the control but had no significant effect on total soil organic carbon, phosphorus absorption, or sweet corn growth and yield. These findings offer valuable insights for optimizing sweet corn cultivation in Ultisols.

Conflicts of interest

The authors declare no conflict of interest.

References

Alemu, E., Selassie, Y. G. and Yetaferu, Y. (2022). Effect of lime on selected soil chemical properties, maize (*Zea mays* L.) yield and determination of rate and method of its application in Northwestern Ethiopia. Heliyon, 8:e08657.

Bharali, A., Baruah, K. K., Bhattacharya, S. S. and Kim, K. H. (2021). The use of *Azolla caroliniana* compost as organic input to irrigated and rainfed rice ecosystems: Comparison of its effects in relation to CH_4 emission pattern, soil carbon storage, and grain C interactions. Journal of Cleaner Production, 313:27931.

Balai Penelitian Tanah. (2009). Technical guidelines for chemical analysis of soil, plants, water and fertilizers (2nd Edition). Balai Penelitian Tanah. ISBN 978-602-8039-21-5.

Casumlong, J. A. M. and Galgo, S. J. C. (2020). Calcium carbonate forms applied to purple sweet corn in Capiz Philippines. International Journal of Bioscience, 17:01-205.

Chen, D., Ye, X., Jiang, Y., Xiao, W., Zhang, Q., Zhao, S., Shao, S., Gao, N., Huang, M. and Hu, J. (2022). Continuously applying compost for three years alleviated soil acidity and heavy metal bioavailability in a soil-asparagus lettuce system. Frontiers, 13:2022.

Costa, M.C.G. (2012). Soil and crop responses to lime and fertilizers in a fire-free land use system for smallholdings in the northern Brazilian Amazon. Soil Tillage Research, 121:27-37.

Dinkecha, K. and Tsegaye, D. (2017). Effects of liming on physicochemical properties and nutrients availability of acidic soils in Walmera Woreda, Central Highlands of Ethiopia. Chemistry and Material Research, 9:30-37.

Ejigu, W., Selassie, Y. G., Elias, E. and Molla, E. (2023). Effect of lime rates and method of application on soil properties of acidic Luvisols and wheat (*Triticum aestivum*, L.) yields in northwest Ethiopia. Heliyon, 9:e13988.

Fahrurrozi, F., Muktamar, Z., Sudjatmiko, S., Chozin, M. and Setyowati, N. (2019). Phosphorus uptakes and yields of sweet corn grown under organic production system. IOP Conference Series: Earth and Environmental Science, 347:012006.

Grieve, I. C., Davidson, D. A. and Bruneau, P. M. C. (2005). Effects of liming on void space and aggregation in an upland grassland soil. Geoderma, 125:39-48.

Herrera, P. M. C. and Perez, L. F. A. (2020). Effect of the liming on the soil chemical properties and the development of tomato crop in Sucre-Colombia. Journal of Applied Biotechnology and Bioengineering, 7:87-93.

Hwang, J. and Son, Y. (2006). Short-term effects of thinning and liming on forest soils of pitch pine and Japanese larch plantations in central Korea. Ecological Research, 21:671-680.

Ifansyah, H. (2013). Soil pH and solubility of aluminum, iron, and phosphorus in Ultisols: The roles of humic acid. Journal of Tropical Soils, 18:203-208.

Jing, J., Zhang, S., Yuan, L., Li, Y., Zhang, Y., Ye, X., Zhang, L., Xiong, Q., Wang, Y. and Zhao, B. (2023). Effects of incorporating different proportions of humic acid into phosphate fertilizers on phosphorus migration and transformation in soil. Agronomy, 3:1576.

Jumadi, O., Hiola, S. F., Hala, Y., Horton, J. and Inubhusi, K. (2014). Influence of Azolla (*Azolla microphylla* Kaulf.) compost on biogenic gas production, inorganic nitrogen and growth of upland kangkong (*Ipomoea aquatica* Forsk.) in a silt loam soil. Soil Science and Plant Nutrition, 60:722-730.

Mahmud, M. S. and Chong, K. P. (2022). Effects of liming on soil properties and its roles in increasing the productivity and profitability of the oil palm industry in Malaysia. Agriculture, 12:322.

Maluf, H. J. G. M., Silva, C. A., Curi, N., Norton, L. D. and Rosa, S. D. (2018). Adsorption and availability of phosphorus in response to humic acid rates in soils limed with $CaCO_3$ or $MgCO_3$. Ciencia e Agrotecnologia, 42:7-20.

Maruapey, A., Soekamto, M. A. and Kella, S. (2022). Utilization of *Azolla pinnata* as compost fertilizer on the growth and production of sweet corn (*Zea mays* Sacchara L.). Median, 14:79-94.

Mijangos, I., Albizu, I., Epelde, L., Amezaga, I., Mendarte, S. and Garbisu, C. (2010). Effects of liming on soil properties and plant performance of temperate mountainous grasslands. Journal of Environmental Management, 91:2066-2074.

Moore, J. D., Ouimet, R. and Duchesne, C. (2012). Soil and sugar maple response 15 years after dolomitic lime application. Forest Ecology and Management, 281:130-139.

Muktamar, Z., Justisia, B. and Setyowati, N. (2016). Quality enhancement of humid tropical soils after application of water hyacinth (*Eichornia crassipes*) compost. Journal of Agricultural Technology, 12:1715-1727.

Muktamar, Z., Adiprasetyo, T., Yulia, Suprapto, Sari, L., Fahrurrozi, F. and Setyowati, N. (2018). Residual effect of vermicompost on sweet corn growth and selected chemical properties of soils from different organic farming practices. International Journal of Agricultural Technology, 14:1471-1482.

Muktamar, Z., Setyowati, N. and Wiyanti, E. (2022). The improvement of selected soil chemical properties using Singapore daisy based compost in Ultisols. International Journal of Agriculture and Biological Sciences, 6:41-48.

Novair, S. B., Hosseini, H. M., Etesami, H. and Razavipour, T. (2020). Rice straw and composted azolla alter carbon and nitrogen mineralization and microbial activity of a paddy soil under drying–rewetting cycles. Applied Soil Ecology, 154:103638.

Olego, M. A., Quiroga, M. J., Cuervo, C. M., Jemenez, J. C., Lopez, R. and Jimeno, E. G. (2021). Long-term effects of calcium-based liming materials on soil fertility sustainability and rye production as soil quality indicators on a Typic Palexerult. Process, 9:1181.

Omenda, J. A., Ngetich, K. F., Kiboi, M. N., Mucheru-Muna, M. W. and Mugendi, D. N. (2021). Phosphorus availability and exchangeable aluminum response to phosphate rock and organic inputs in the Central Highlands of Kenya. Heliyon, 7:e0637.

Paradelo, R, Virto, I. and Chenu, C. (2015). Net effect of liming on soil organic carbon stocks: A review. Agriculture, Ecosystems & Environment, 202:98-107.

Rahman, S. U., Han, J. C., Ahmad, M., Ashraf, M. N., Khaliq, M. A., Yousaf, M., Wang, Y., Yasin, G., Nawaz, M. F., Khan, K. A. and Du, Z. (2024). Aluminum phytotoxicity in acidic environments: A comprehensive review of plant tolerance and adaptation strategies. Ecotoxicity and Environmental Safety, 269:115791.

Rashid, N. S. A., Jalloh, M. B., Azman, E. A., Awang, A., Ahmed, O. H. and Tajidin, N. E. (2024). Effects of fresh and composted *Azolla* on soil chemical properties. Pertanika Journal of Tropical Agricultural Science, 47:291-1308.

Said, D. S., Chrismadha, T., Mardiati, Y. and Mayasari, N. (2023). Nutritional content and growth ability of aquatic plant *Azolla pinnata* on wastewater of catfish. IOP Conference Series: Earth and Environmental Science, 1260:1-13.

Sambodo, A. N., Sudadi. and Sumarono. (2014). The effect of azolla- based organic fertilizer, rock phosphate and rice husk ash to peanut in Alfisols. Caraka Tani-Journal of Sustainable Agriculture, 29:73-80.

Seleiman, M. F., Elshayb, O. M., Nada, A. M., El-leithy, S. A., Baz, L., Alhammad, B. A. and Mhadi, A. H. A. (2022). Azolla compost as an approach for enhancing growth, productivity and nutrient uptake of *Oryza sativa* L. Agronomy, 12:416.

Shetty, R., Vidya, C. S. N., Parkash, N. B., Lux, A. and Vaculik, M. (2021). Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. Science of the Total Environment, 765:142744.

Sidahmed, H. M. I., Illés, Á., ALmahi, A. and Nagy, J. (2024). Performance of agricultural factors on yield of sweet corn (*Zea mays* L. Saccharata) - A review. Acta Agraria Debreceniensis, 1:143-156. https://doi.org/10.34101/actaagrar/1/12830

Sidahmed, H., Vad, A. and Nagy, J. (2025). Advances in sweet corn (*Zea mays* L. saccharata) research from 2010 to 2025: genetics, agronomy, and sustainable production. Agronomy, 15:1260. https://doi.org/10.3390/agronomy15051260

Spark, D. L. (2003). Environmental Soil Chemistry. Second ed. Academic Press. New York. USA.

Sramek, V, Fadrhonsova, V., Vortelova, L. and Lomsky, L. (2012). Development of chemical soil properties in the western Ore Mts. (Czech Republic) 10 years after liming. Journal of Forest Science, 58:57-66.

Swami, S. and Singh, S. (2019). Harnessing production potential of acidic soils: Impacts of Azolla (*Azolla pinnata*) bio-fertilizer and urea on rice (*Oryza sativa* L.) performance, temporal soil P availability and acidity indices. South Asian Research Journal of Agriculture and Fisheries, 1:1-8.

Uchida, R. (2000). Essential nutrient for plant growth: Nutrient functions and deficiency symptoms. In: Plant Nutrition Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture. JA. Silva and R. Uchida (eds). College of Tropical Agriculture & Human Resources. University of Hawaii at Manoa. Chapter, 3:31-55.

Yi, C., Zhu, J., Chen, L., Huang, X., Wu, R., Zhang, H., Dai, X. and Liang, J. (2023). Speciation of iron and aluminum in relation to phosphorus sorption and supply characteristics of soil aggregates in subtropical forests. Forest, 14:1804.

Zhang, S., Zhu, Q., Vries, W., Ros, G. H., Chen, X., Muneer, M. A., Zhang, F. and Wu, L. (2023). Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis. Journal of Environmental Management, 341:118531.

(Received: 7 July 2025, Revised: 20 December 2025, Accepted: 1 January 2026)