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Impact of Food Waste-Derived Sandwiched Compost on Soil Properties and Nutrient Uptake in *Brassica rapa* subsp. chinensis (Bok Choy)

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ABSTRACT

Food waste generation is an urgent environmental problem that troubles the waste management systems and destroys the ecosystem. To get as a sustainable alternative, sandwiched compost, is a modified Bokashi-based composting method that transforms food waste into nutrient-rich organic fertilizer for plant growth. This study studied the effects of sandwiched compost on plant-soil nutrients with bok choy from the four sequential growing cycles. The leachate from the sandwiched compost was amended as a seed priming agent and liquid fertilizer, whereas the compost was amended as a soil amendment. The significant findings showed that amending sandwiched compost to the soil improved the pH range (6.0–7.5), diminished aluminum toxicity, and escalated the availability of nutrients like iron (Fe), silicon (Si), and phosphorus (P). This amendment is evidence of an antagonistic interaction between potassium and calcium (Ca) decreased plant Ca absorption. In short, sandwiched compost significantly boosted plant nutrient uptake and soil fertility, showing its potential as an environmentally acceptable substitute for traditional fertilizers. To address Ca antagonism and enhance its agricultural applications, further studies should focus on optimizing nutrient balance.

Keywords: Soil fertility improvement, plant nutrient uptake, cation exchange capacity, soil pH optimization, sustainable agriculture

INTRODUCTION

Commercial fertilizers were launched years ago to improve soil nutrients to meet the demand for nutritious food production (Usman *et al.* 2020). Yet, their extensive use significantly impacts environmental and human health. Overfertilization affects soil salinity, water eutrophication, and the accumulation of heavy metals and nitrates (Savci 2012). For instance, excessive fertilizer application reduces crop yields, which is observed in cucumbers (Chen *et al.* 2024). The potential of organic fertilizers, for example, compost, is still under-studied, especially innovative methods like Sandwiched composting, despite the environmental issues linked to commercial fertilizers.

To promote environmental conservation, transitioning to organic fertilizers is vital for sustainable food production and aligns with Malaysia's Agricultural Good Practices (myGAP). Compost enriches soil with essential nutrients and trace elements, and strengthens soil structure by reinforcing water-stable aggregates and reducing bulk density (Chen *et al.* 2024). Its high humic acid content further enhances soil porosity and stability, nurturing long-term soil health. In addition, biofertilizer amendments significantly increase microbial biomass and activity, and thus improve soil fertility (Javoreková *et al.* 2015). Mixing organic matter with commercial fertilizers enhances crop yields (Chen *et al.* 2024). However, the enduring global provocation of food waste requires sustainable management at the source, usually associated with consumer consumption behaviors. Traditional waste management, for instance, landfilling and incineration, is unsustainable, worsening environmental degradation (Azizan and Hussin 2015; Hashim *et al.* 2021; Yoong *et al.* 2022).

Sandwiched composting, a modification of Bokashi composting, shows a feasible solution for breaking down cooked and uncooked food waste. This method provides an efficient alternative to conventional composting practices. This study focuses on the amendment of food waste-derived Sandwiched compost for agricultural purposes because of its potential to address food waste and enhance soil fertility, Bok choy was chosen as the test crop due to its rapid growth cycle and high market demand. Furthermore, Bok choy's act on soil amendments makes it an ideal candidate for assessing compost effectiveness. This study studied the impact of Sandwiched compost on soil and plant nutrients over four consecutive Bok choy growing cycles. The study objectives are to donate to sustainable good agricultural practices and align with global efforts to decrease food waste and thus promote organic farming by studying compost's role in improving soil health and crop productivity.

MATERIALS AND METHODS

Study site

The experiment was done in a greenhouse, Field 10, Universiti Putra Malaysia (UPM), with the coordinate of latitude 2°59'31.4"N and longitude 101°42'52.1"E. The temperature was 28±4 °C, and the relative humidity was 70±10 %. The studied soil was collected from the study site and analyzed for physical (texture) and selected chemical characteristics (**Table 1**).

Table 1. The pre-amended soil Physico-chemical parameter.

Physico-chemical parameter	Pre-amended soil
Texture (Teh and Talib, 2006)	Clay
pH	4.00±0.0473*
Cation exchange capacity (cmolc kg^{-1})	7.6±0.216
Total N (%)	0.12±0.0035
Available P (mg kg^{-1})	3.92±0.06387
Exchangeable K (cmolc kg^{-1})	0.581±0.0265
Exchangeable Ca (cmolc kg^{-1})	0.213±0.0209
Exchangeable Mg (cmolc kg^{-1})	0.867±0.0174
Exchangeable Na (cmolc kg^{-1})	Not detected
Extractable Cu (mg kg^{-1})	1.36±0.0498
Extractable Fe (mg kg^{-1})	48.6±1.01
Extractable Al (mg kg^{-1})	1321±27.4
Extractable Si (mg kg^{-1})	16.13±0.1169

Amendments and experimental design

Sandwiched compost was prepared using cooked and uncooked food waste (Christel 2017 Jan 1; Phooi *et al.* 2021). Bok choy was subjected to amendments mixing Sandwiched compost substrate and leachate (**Table 2**) to study their individual and combined effects on plant growth and soil properties.

Table 2. Amendment combinations and justifications

Amendments	Substrate	Leachate (seed priming)	Leachate (liquid fertilizer)	Description
T000	No	No	No	Negative control (baseline)
T001	No	No	Yes	Tests leachate as fertilizer
T009	Commercial			Positive control (standard fertilizer)
T010	No	Yes	No	Tests leachate for seed priming
T011	No	Yes	Yes	Combined leachate effects
T100	Yes	No	No	Tests compost substrate alone
T101	Yes	No	Yes	Substrate + leachate fertilizer
T110	Yes	Yes	No	Substrate + seed priming
T111	Yes	Yes	Yes	Full amendment (all factors)

For substrate amendments (**Table 3**), 1.3 kg of Sandwiched compost was mixed with soil in 10 × 10 cm polybags, layered with 0.7 kg urban soil, and sealed. Substrate was applied once at the start. Bok choy was grown over four cycles. For seed priming, before sowing in peat moss trays, 1 g of seeds was soaked in 500 mL of tap water (**Table 3**) with 1 mL of 0.2% Sandwiched compost leachate for 3 hours (54 × 35 × 4 cm). Germination took place under a 16:8 h light/dark cycle at 32°C (day) and 28°C (night). Seedlings were transplanted after 45 days of soil incubation. Leachate (0.2%) was applied at five-day intervals starting 8 days after transplanting (DAT).

Table 3. Physico-chemical parameters of tap water, Sandwiched compost substrate and leachate (mean ± standard error) with 4 replications.

Physiochemical parameter	Tap water	Sandwiched compost substrate	Sandwiched compost leachate
pH	6.98±0.02		4.78±0.011
Total N (%)	0.00056±1.63×10-18	1.722±0.2560	0.2135±0.0052
P (mg kg^{-1})	0.0447±0.0197	16397±543	5833±223
K (mg kg^{-1})	3.64±0.0415	20799±1230	3941±131
Ca (mg kg^{-1})	13.8±0.150	5935±183	528±18.6
Mg (mg kg^{-1})	1.01±0.0111	4870±218	1249±53.9
Fe (mg kg^{-1})	0.306±0.015	360±37.3	160±42.5
Al (mg kg^{-1})	Not detected	10050±94.4	770±510
Si (mg kg^{-1})	6.60±0.256	19.7±0.915	

Soil chemical analysis

Oven-dried samples were ground (stainless-steel coffee grinder) and stored in plastic bags. A 0.25 g sample was digested using a 1:1 H2SO4:H2O2 solution at 350°C until colorless. After cooling, the digest was diluted with distilled water, filtered (No. 1 filter paper), and analyzed for P, K, Mg, Ca, Fe, Al, and Si using ICP-OES (Optima 8300, Perkin Elmer, USA). Nitrogen (N) was determined by Kjeldahl distillation and titration with 0.01 N HCl, which follows a standard method (Bremner, 1960).Soil pH was measured in a 1:2.5 soil-to-water ratio. A 10 g soil sample was mixed with 25 mL distilled water, shaken (150 rpm, 30 min), left to stand for 24 hours, and measured using a pH meter (Xu *et al.* 2020).CEC and exchangeable bases were determined by ammonium acetate leaching (pH 7) and quantified by ICP-OES. Distillation with NaOH and titration with HCl followed to determine CEC (Rhoades 1982). Results were expressed in cmol/kg.Total N was analyzed by the Kjeldahl method. A 1 g soil sample was digested overnight in H_2SO_4 with salicylic acid, Na2S2O3, and Kjeldahl tablets until clear. Distillation and titration with 0.01 N HCl followed (Bremner 1960). Available P was determined colorimetrically by the Murphy and Riley (1962) method. Soil was extracted with a 1:7 HCl-H4F solution, reacted with ammonium molybdate, antimony potassium tartrate, and ascorbic acid, and absorbance was measured at 885 nm.Micronutrients were extracted using Mehlich-3 solution (Fe, Mn, and Zn) followed Mehlich 3 with modification (Mehlich 1984; Minca *et al.* 2013). A 1:10 soil-to-extractant ratio was shaken (15 min, 180 rpm), filtered, and analyzed by ICP-OES.Si was extracted with 0.01 M CaCl2 (16 hours, end-over-end shaker), centrifuged (2000 rpm, 10 min), and analyzed by ICP-OES (Elliott and Snyder 1991).

Statistical analysis

The collected data were subjected to statistical analyses with two-way Analysis of Variance (ANOVA) using R-program statistic software. When F was significant at the $p<0.05$ level, amendment means were compared and separated using the Duncan Mean Range Test (DMRT). The results were expressed as mean ± standard error of measurement.

RESULTS

Soil pH

Soil pH showed a significant interaction between the growing cycle and Sandwiched compost amendments (**Figure 1**). In the absence of compost amendments, soil pH remained consistent with the pre-amended level (pH 4.0). Whereas soils amended with Sandwiched compost showed a significant increase in pH, maintaining values within the optimal range for plant growth (pH 6.0–7.5) along the four growing cycles (Table 1).

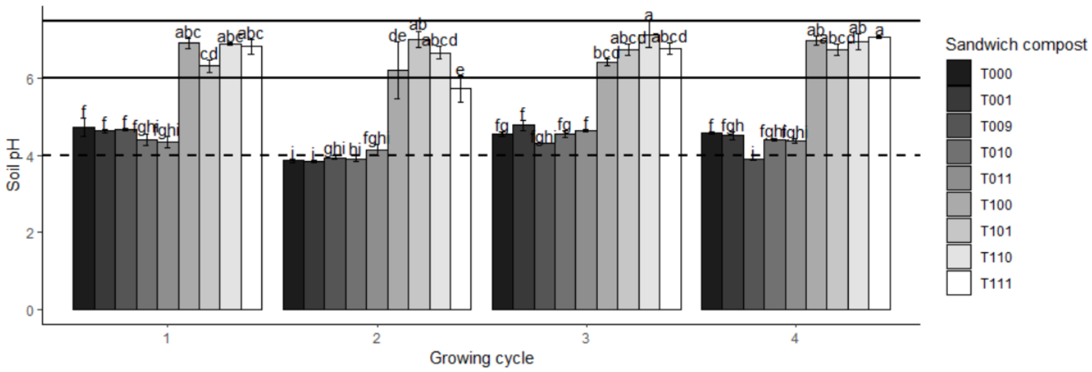

Figure 1. Effect of the growing cycle and Sandwiched compost amendments on soil pH. Means ± standard error with different letters are significantly different at P < 0.05 using DMRT. The dotted line indicates pre-amended soil pH (4.0), and the solid lines represent the optimal pH range (6.0–7.5).

Soil cation exchangeable capacity

CEC did not show a significant interaction between the growing cycle and compost amendment (**Figure 2**). However, significant main effects were observed. CEC decreased significantly by the fourth growing cycle (**Figure 2A**), while compost-amended soils showed consistently higher CEC levels compared to unamended soils and pre-amended conditions (**Figure 2B**).

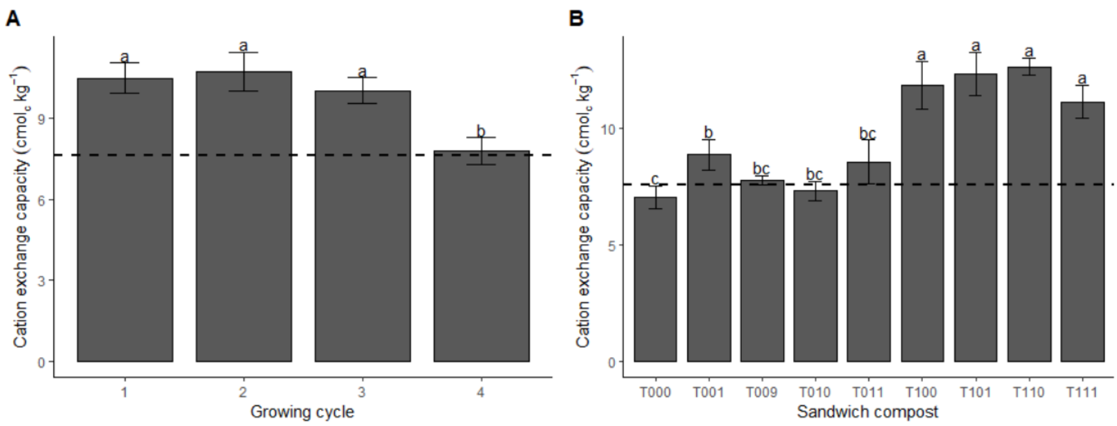

Figure 2. Effect of (A) growing cycle and (B) Sandwiched compost amendments on cation exchange capacity (cmolc kg⁻¹). Means ± standard error with different letters are significantly different at P < 0.05 using DMRT. The dotted line indicates pre-amended soil CEC (7.6 cmolc kg⁻¹).

Soil macronutrients

Soil macronutrients such as total N (**Figure 3**), available P (**Figure 4**), exchangeable K (), Ca (**Figure 6**), and Mg (**Figure 7**) exhibited significant interactions between the growing cycle and Sandwiched compost amendments. Compost-amended soils exhibited significant escalation in total N, peaking during the third growing cycle. In unamended soils, total N decreased after plant growth. Compared to unamended soils and pre-amended conditions, compost-amended amendments (T100, T101, T110, and T111) consistently exhibited higher available P levels. The highest available P levels were noted for T100 in cycle 1, T101 in cycle 2, and T110 in cycle 3. Compost-amended soils had significantly higher exchangeable K than unamended soils and pre-amended soil conditions. The highest exchangeable K was shown in T101 during the second growing cycle. With peak levels observed during the fourth growing cycle, compost-amended soils consistently showed higher exchangeable Ca compared to unamended soils. Compost-amended soils evident significantly higher exchangeable Mg than unamended soils. The highest exchangeable Mg levels were documented in T101 during the second growing cycle.

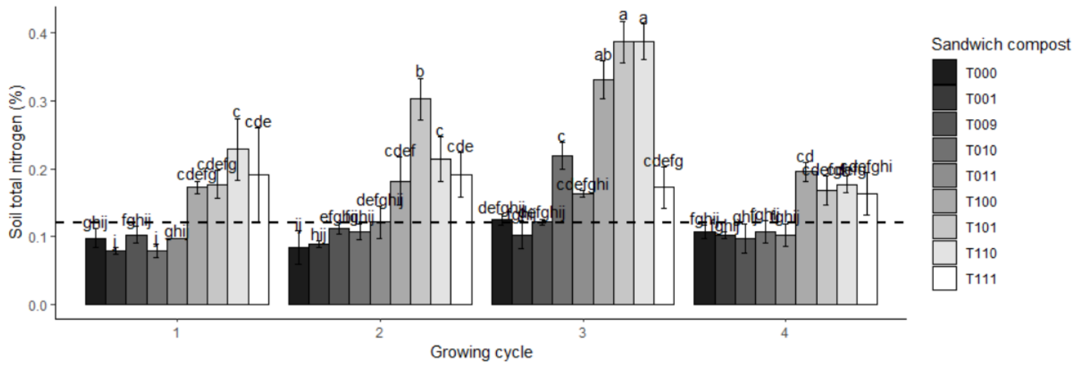

Figure 3. Effect of the growing cycle and Sandwiched compost amendments on soil total nitrogen under 4 growing cycles.

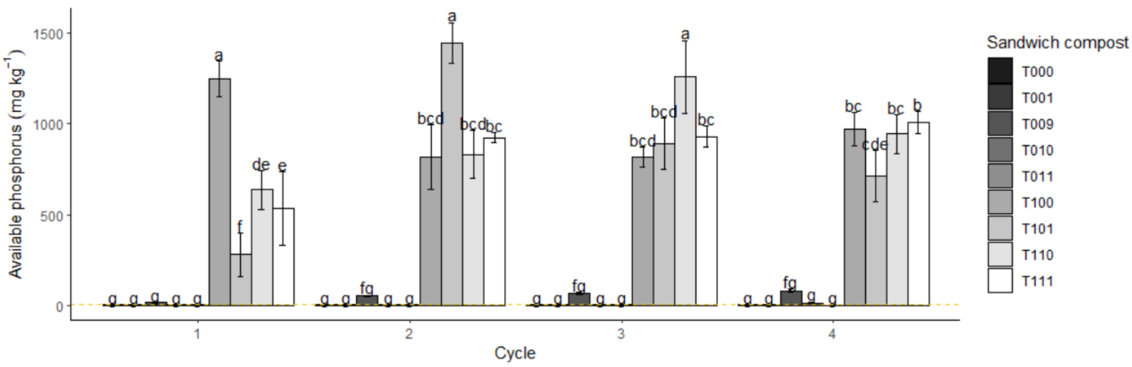

Figure 4. Effect of the growing cycle and Sandwiched compost amendments on available P under 4 growing cycles.

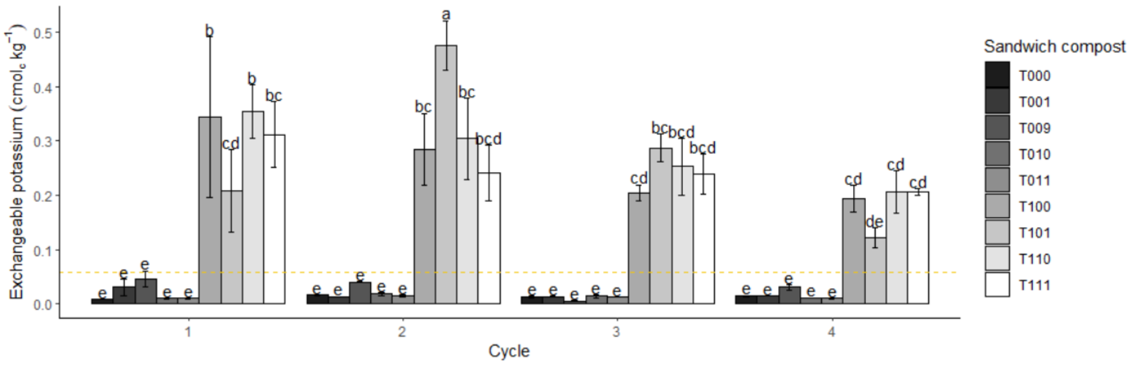

Figure 5. Effect of the growing cycle and Sandwiched compost amendments on exchangeable K under 4 growing cycles.

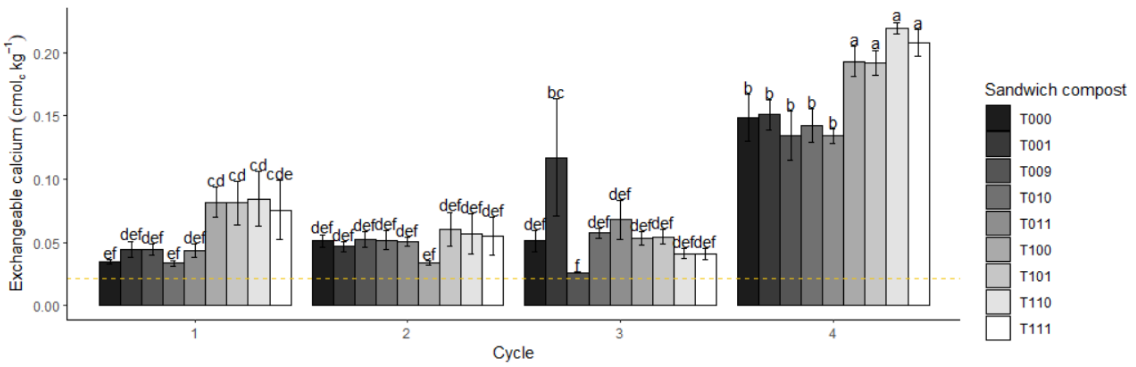

Figure 6. Effect of the growing cycle and Sandwiched compost amendments on exchangeable ing cycles.

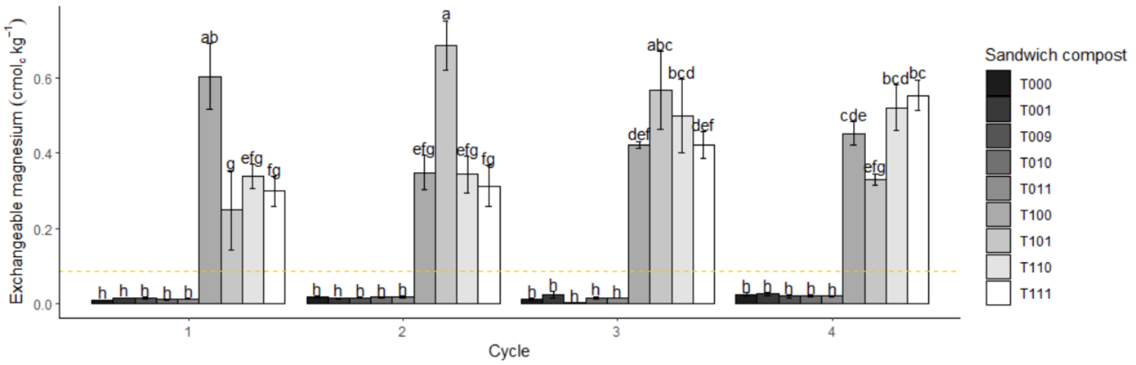

Figure 7. Effect of the growing cycle and Sandwiched compost amendments on exchangeable Mg under 4 growing cycles.

Soil micronutrients

Soil micronutrients, such as available Fe (**Figure 8**), Al (**Figure 9**) and Si (**Figure 10**), exhibited significant differences based on compost amendment and growing cycles. Compared to unamended soils and pre-amended conditions, compost-amended soils (T100, T101, T110, and T111) consistently showed significantly higher available Fe. Compost-amended soils showed lower available Al levels compared to unamended soils. Available Al increased in unamended soils during the fourth growing cycle, reaching levels similar to pre-amended soil.

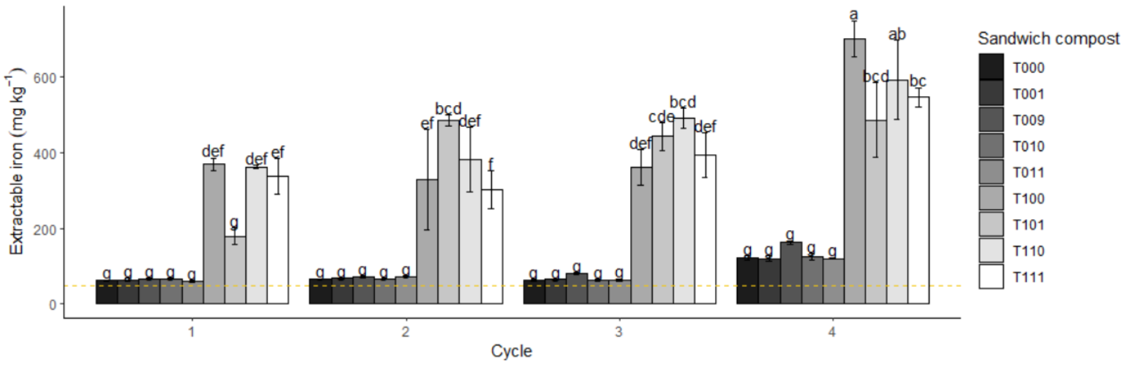

Figure 8. Effect of the growing cycle and Sandwiched compost amendments on extractable iron (Fe) under 4 growing cycles.

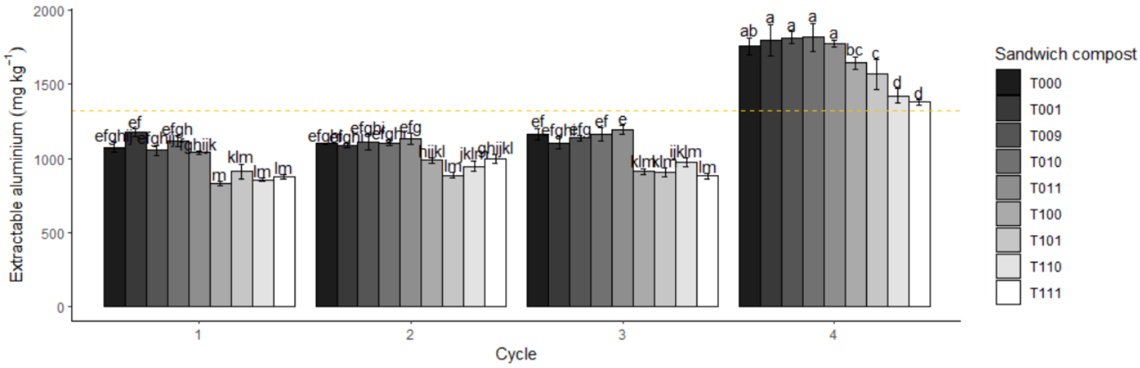

Figure 9. Effect of the growing cycle and Sandwiched compost amendments on available aluminium (Al) under 4 growing cycles.

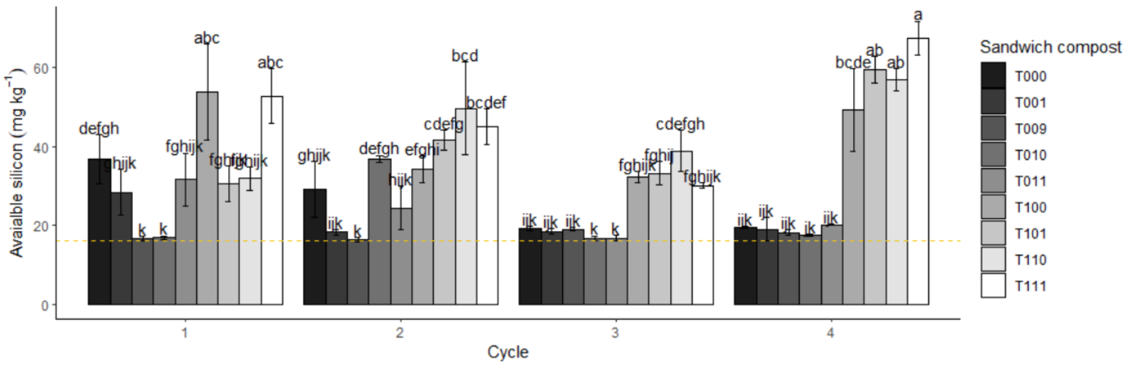

Figure 10. Effect of the growing cycle and Sandwiched compost amendments on available silicon (Si) under 4 growing cycles.

Plant nutrients

Plant nutrient concentrations significantly differ across growing cycles and compost amendments. Plant N showed no significant interaction between the growing cycle and compost amendment (Table 4). Yet, N concentrations peaked during the third growing cycle. Among amendments, T009 (commercial fertilization) exhibited the highest total N. Compost-amended soils showed an incremental increase in plant P concentrations, significantly exceeding levels in unamended soils (Figure 11). T009 kept constant plant P levels across all cycles. Compost-amended soils resulted in significantly higher plant K levels compared to unamended soils (Table 4). T101 exhibited the highest plant K levels during the second growing cycle. Compost-amended soils resulted in lower plant Ca concentrations compared to unamended soils. The highest plant Ca levels were observed during the third growing cycle (**Table 4**). Compost-amended soils significantly boosted plant Mg concentrations compared to unamended soils (**Figure 12**). Plant Al concentrations were significantly reduced in compost-amended soils and decreased during the first three growing cycles (**Figure 13**). Unamended soils exhibited the highest Al concentrations, especially in T000 and T001. Plant Fe concentrations peaked during the third growing cycle, with compost-amended soils showing higher levels compared to unamended ones (**Figure 14**). With no significant differences observed between amendments, plant Si levels remained consistent across growing cycles (**Figure 15**).

Table 4. Single effect of the growing cycle and Sandwich compost treatments on nitrogen, calcium and potassium. Means with different letters are significantly different at P<0.05 using DMRT.

Cycle	**N (%)**	**K (mg kg^{-1})**	**Ca (mg kg^{-1})**
1	3.055 b	30387.51 d	12740.18 c
2	2.518 c	40735.63 c	16965.87 b
3	4.331 a	62520.48 a	20334.66 a
4	2.791 bc	47275.32 b	17892.86 b
Pr(>F)	<2e-16 ***	<2e-16 ***	6.17E-09
Treatment			
T000	3.233 bc	31863.17 c	22100.52 a
T001	3.35 b	31264.26 c	22323.31 a
T009	3.83 a	53477.06 b	18319.93 b
T010	2.913 bc	30606.25 c	21302.79 ab
T011	2.997 bc	26869.78 c	21436.49 ab
T100	3.102 bc	57216.44 b	12745.97 c
T101	3.032 bc	66602.4 a	12021.26 c
T110	3.293 bc	53725.49 b	11736.68 c
T111	2.815 c	55442.8 b	10863.59 c
Pr(>F)	0.001899 **	<2e-16 ***	7.97E-16
R Square	0.763	0.836	0.779
Mean	3.173883	45229.74	16983.39
CV	17.70462	22.98884	22.6237

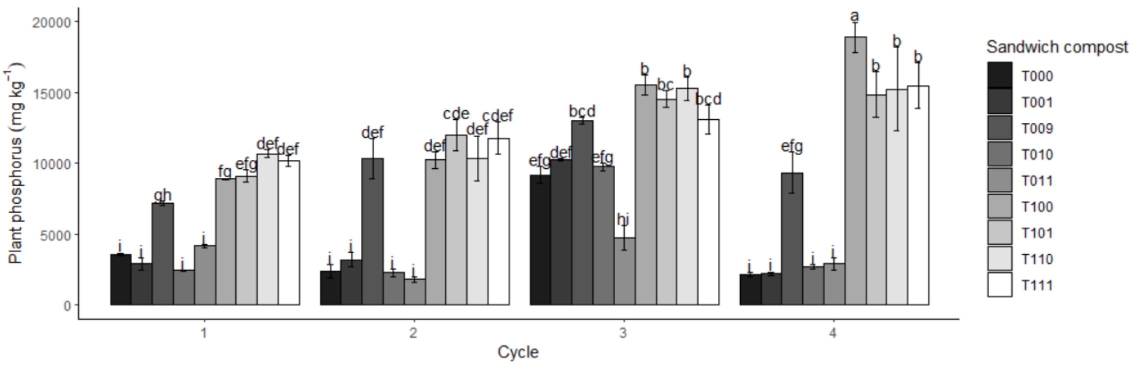

Figure 11. Effect of the growing cycle and Sandwiched compost amendments on plant phosphorous under 4 growing cycles.

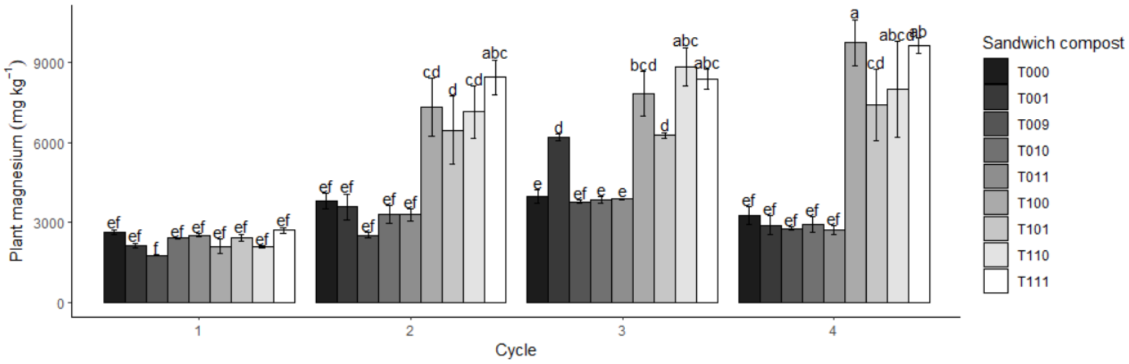

Figure 12. Effect of the growing cycle and Sandwich compost on plant magnesium (mg kg^{-1}). Means ± standard error with different letters is significantly different at P<0.05 using DMRT.

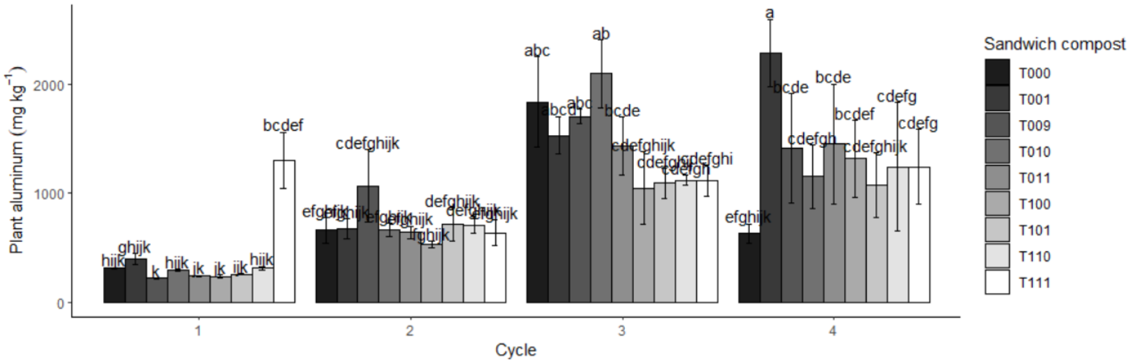

Figure 13. Effect of the growing cycle and Sandwich compost on plant aluminium (Al) (mg kg^{-1}). Means ± standard error with different letters is significantly different at P<0.05 using DMRT.

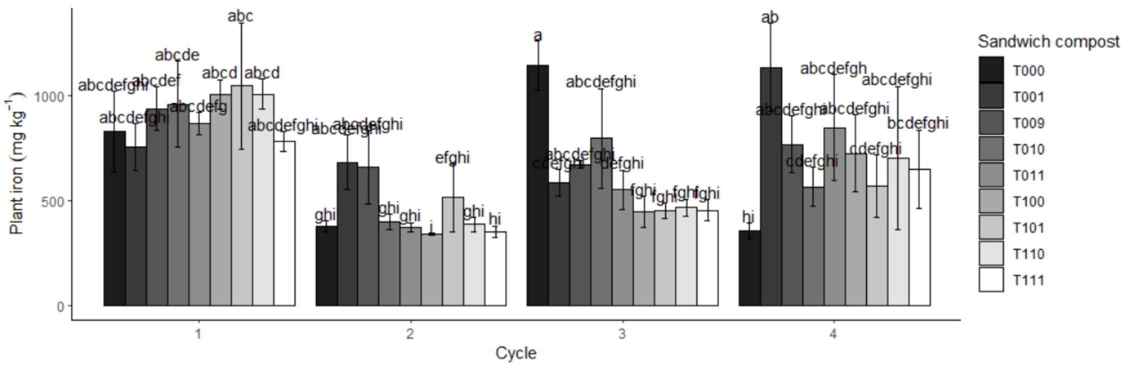

Figure 14. Effect of the growing cycle and Sandwich compost on plant iron (Fe) (mg kg$^{-1)}$. Means ± standard error with different letters is significantly different at P<0.05 using DMRT.

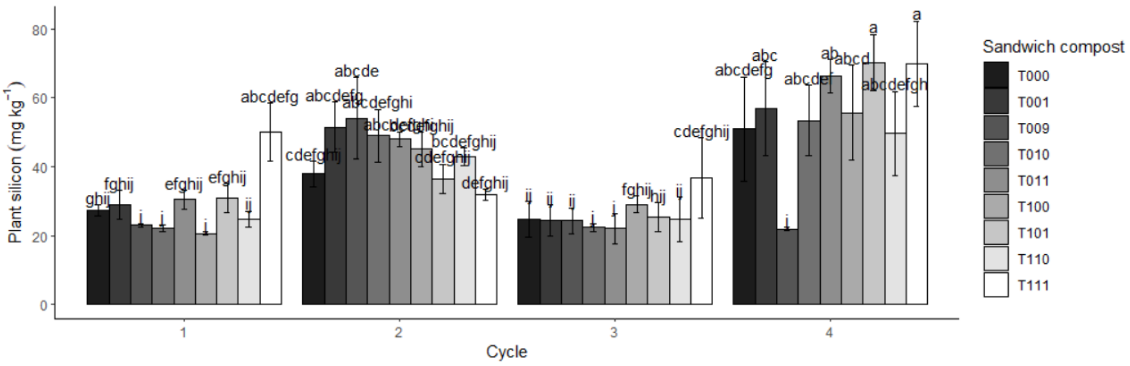

Figure 15. Effect of the growing cycle and Sandwich compost on plant silicon (mg kg^{-1}). Means ± standard error with different letters is significantly different at P<0.05 using DMRT.

DISCUSSION

Soil pH neutralized and availability of aluminium reduced with Sandwiched compost amendment

The pre-amended soil pH of 4.0 was unsuitable for most plants to grow. The application of Sandwiched compost significantly increased soil pH to a range between 6.0 and 7.0, which is optimal for plant nutrient availability and nitrogen uptake (Ma *et al.* 2017). This result aligns with findings from studies on compost amendment (Eghball *et al.* 2004; Christel 2017 Jan 1; Prayogo and Ihsan 2018; Setyastika and Suntari 2019). Organic matter in compost reduced aluminum toxicity, mimicking the effects of liming by binding aluminum and releasing previously immobilized phosphorus (Ahmad and Tan 1986).

Neutralizing soil pH also boosts microbial biomass (Zhalnina *et al.* 2015) and enzyme activity (Wolinska and Stepniewsk 2012), which are vital for nutrient cycling. In addition, higher pH improved the availability of iron (Fe) and manganese (Mn) for plant uptake (Prayogo and Ihsan 2018). Moreover, a neutral pH environment advantages soil fauna, such as earthworms, which are negatively impacted by an acidic environment and high aluminum sulfate concentrations (Van Gestel and Hoogerwerf 2001). These findings are aligned with previous studies, underscoring the multi-benefits of pH adjustment through organic amendments.

Soil cation exchangeable capacity increased with the Sandwiched compost amendment

Because of the organic matter degradation, CEC increased in soils amended with Sandwiched compost however declined during the fourth growing cycle. This consistent with previous findings that prolonged compost degradation reduces the organic matter's ability to retain cations (Fornes *et al.* 2012). The high CEC observed in earlier cycles is due to organic matter-derived negatively charged sites, such as lignin derivatives and humic substances (Parfitt *et al.* 1995; Kweon *et al.* 2013; Lyu *et al.* 2021).

The humification process in Sandwiched compost leads to the formation of phenolic and carboxylic functional groups, further improving the soil's cation retention capacity (Benito *et al.* 2009). These findings align with studies stressing compost's role in improving soil physicochemical properties (Gallardo-Lara and Nogales 1987; Parfitt *et al.* 1995; Silber *et al.* 2010).

Nitrogen in soil improved with Sandwiched compost amendment but not in plant
Even though Sandwiched compost increased soil total nitrogen (N), plant N levels did not reflect this improvement. The reduced plant N uptake may be clarified by antagonistic nutrient interactions or microbial immobilization of N. Luxury uptake by microbes if excessive N is available, slowing N mineralization and eventually reducing plant N absorption (Fog 1988). Similar findings have been shown with high-organic amendments like manure and sewage sludge (Ciampitti and Lemaire 2022).

Excess N may disrupt carbohydrate (CHO) allocation and phosphorus (P) uptake, limiting plant reproductive growth and overall health (Lastdrager *et al.* 2014) which suggests that while Sandwiched compost improves soil N retention, its benefits may not be fully applied for plant uptake unless microbial community dynamics and nutrient balance are optimized.

Phosphorus in soil and plant improved by Sandwiched compost application
Soil phosphorus (P) levels were highest across the four growing cycles, aligned with studies showing that compost amendments provide sustained P availability (Eghball *et al.* 2004). Sandwiched compost enhanced biological P mineralization via P-related microbial activity, which improved plant P uptake efficiency (Oberson *et al.* 2001).

Compost-amended soils have improved microbial biomass P and plant P levels, particularly when high-P materials like livestock manure are used (He *et al.* 1997; Takeda *et al.* 2009). Compared to commercial fertilizers, Sandwiched compost prolonged higher P availability because inorganic P fertilizers are usually fixed with aluminum and iron components, reducing their bioavailability rapidly (Johan *et al.* 2021).

Potassium, calcium and magnesium in soil and plant
Sandwiched compost significantly increased exchangeable potassium (K), calcium (Ca), and magnesium (Mg) levels in soil. Nevertheless, K exhibited susceptibility to leaching during irrigation, consistent with its lower adsorption affinity compared to polyvalent cations like Ca^{2+} and Mg^{2+} (Gerzabek 2018).

Remarkably, while soil Ca levels increased, plant Ca uptake was lower, this is because of the antagonistic interactions with K and Mg (Fageria 2001). This phenomenon aligns with studies showing that high K concentrations suppress Ca uptake (Rhodes *et al.* 2018). However, further study into the biochemical mechanisms based on this antagonism in Sandwiched compost-amended soil is required.

Plant silicon increased from growing cycle to growing cycle by Sandwiched compost amendment
Soil silicon (Si) levels increased with Sandwiched compost, consistent with findings that rice straw compost enhances plant Si availability (Watanabe *et al.* 2017). While Bok Choy, as a dicot, is a low Si accumulator, increased soil bioavailable Si likely promoted plant structural integrity and photosynthetic efficiency (Senthilkumar *et al.* 2021). Continuous long-term compost amendments have been shown to prolong soil Si availability, supporting the use of organic inputs for improving Si nutrition in crops (Noriko *et al.* 2006).

CONCLUSION

Amending soil with Sandwiched compost shifted soil pH to the optimal range (pH 6–7.5) effectively, significantly reducing soil aluminum availability and thus improving the availability of macronutrients such as phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), and silicon (Si). Despite the antagonistic interaction between K and calcium (Ca) reduced plant Ca levels regardless of rose exchangeable Ca in the soil, the soil improvement decoded into higher plant uptake of P, K, Mg, and Si.

Thus, Sandwiched compost can act as a potential sustainable soil amendment to improve nutrient availability and soil health, reducing the need for commercial fertilizers and conserving the environment for future generations. Nonetheless, managing nutrient antagonisms remains a fussy challenge, therefore, further studies can focus on optimizing compost composition, amendment timing, and rate to reduce nutrient competition and ensure plant nutrition balance and ultimately for the optimum plant yield.

Not only that, long-term studies are needed to assess the long-term effects of Sandwiched compost amended on soil fertility, crop yield, and also environmental sustainability under different agroecological environments. These findings could affect the development of integrated good soil fertility management practices, providing handy advantages for farmers and policymakers' objective to increase the yield while maintaining ecological balance.

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