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Short-term amelioration of acidic subsoil using dairy farm effluent compost and humic acid: a laboratory incubation study

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Abstract: Acidic subsoils pose a significant challenge to sustainable agriculture production due to poor nutrient availability and limited productivity, particularly in regions like Malaysia with tropical climates. This incubation study explored the potential of dairy farm effluent compost (DFEC) and humic acid (HA) as organic amendments to ameliorate acidic subsoil, focusing on improving soil chemical properties while reducing fertilizer use. The experiment evaluated five treatments with varying combinations of DFEC, HA, and reduced fertilizer rates (50% and 75%) under controlled laboratory conditions. Soil samples were analysed for pH, organic matter (OM), macronutrient (N, P, K, Ca, Mg) and other selected elements (Al, Fe, Na, Cu, and Zn) concentrations across a 90-day period. The results revealed that while soil pH showed insignificant changes, treatments with DFEC and HA significantly enhanced soil OM and macronutrient levels, particularly N, P, K, and Ca. Treatment 4 (DFEC + HA with 50% fertilizer reduction) was identified as the better combination, demonstrating the best improvements in subsoil nutrient content. Sodium (Na) levels initially increased in DFEC-treated soils but declined over time, possibly driven by decomposition and adsorption processes. Micronutrient dynamics varied, with Al and Fe exhibiting fluctuating trends influenced by soil pH and redox reactions. Trace metals such as Cu and Zn were minimally affected, with Cu concentrations declined possibly due to immobilization processes. In general, study suggest possible long-term benefits of DFEC and HA in promoting nutrient retention, and organic matter enrichment. It provides insights into soil amendment strategies for subsoil rejuvenation, contributing to sustainable agricultural practices in tropical regions. Further research, including pot and field trials, is needed to evaluate the long-term effects and mechanisms in the presence of crops.

Keywords: organic amendments, soil chemical properties, subsoil rejuvenation, sustainable agriculture

1. Introduction

Soil erosion is a pressing global issue that threatens food security, environmental sustainability, and economic stability. Soil erosion depletes fertile topsoil, disrupts nutrient cycles, and causing land degradation, leaving subsoil exposed (Kumar et al., 2024). In regions prevalent in tropical and subtropical climates with acidic subsoil such as Malaysia, the combined effects of erosion and subsoil acidity reduce nutrient availability and disrupt sustainable agricultural practices (Faridah et al., 2022). Acidic subsoils, characterized by low pH and toxic levels of aluminum,

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pose challenges for farmers worldwide, especially in regions with high rainfall and intensive farming activities (Zhu & Shen, 2024). Restoring acidic subsoils for growing crops is therefore critical to maximizing land use and ensuring long-term agricultural viability. Addressing this issue requires innovative and sustainable approaches to restore soil health while minimizing environmental impacts.

In Malaysia, acidic subsoils are a common problem due to the country's tropical climate (Faridah et al., 2022), which accelerates soil acidification through leaching and weathering processes. This issue is further worsened by the widespread use of chemical fertilizers, which, while essential for boosting yields, often lead to nutrient imbalances and contribute to environmental pollution (Pandian et al., 2024). The agricultural sector in Malaysia plays a vital role in ensuring food security and supporting livelihoods, making the rehabilitation of degraded soils a critical priority. However, sustainable solutions for soil restoration must balance agricultural productivity with environmentally friendly practices to align with global sustainability goals.

Among various soil amendments, dairy farm effluent compost (DFEC) has emerged as a promising solution. This organic by-product of dairy farming is rich in nutrients, organic matter, and microbial activity, making it suitable for improving soil structure and enhancing soil fertility to support plant growth (Maludin et al., 2019). Dairy farm effluent compost not only reduces soil acidity but also enhances the water-holding capacity and promotes beneficial microbial populations (Smith & Collins, 2007). Its application as an organic amendment aligns with the principles of sustainable agriculture by reducing reliance on chemical fertilizers and recycling agricultural waste.

Another valuable amendment for soil restoration is humic acid (HA), a naturally occurring organic compound derived from the decomposition of plant and animal matter (Gupta et al., 2021). Humic acid possesses unique properties that make it an effective soil conditioner (Bhatt & Singh, 2022), including its ability to chelate harmful metals like aluminum, which are prevalent in acidic subsoils. Additionally, HA improves soil aggregation, enhances nutrient retention, and stimulates root development, thereby creating a more favourable environment for crop growth (Ampong et al., 2022). The synergistic effects of HA with other soil amendments further amplify its restorative potential.

By examining the combined application of DFEC and HA, this laboratory incubation study aimed to determine their effects on selected chemical properties of a weathered acidic subsoil under controlled conditions. By reducing fertiliser application rates to 75% and 50%, the research assessed the potential of these organic amendments to enhance soil nutrients retention and organic matter content, addressing the challenges of subsoil degradation. This investigation provides a foundation for developing sustainable soil management strategies, targeting for improving agricultural productivity, and set pathway for subsequent study to validate these findings in field settings.

2. Materials and Methods

The soil used in this study was Ultisol (Silabukan association), collected from Universiti Malaysia Sabah, Faculty of Sustainable Agriculture in Sandakan, Malaysia (5°55'54.6"N, 118°00'13.9"E). Samples were randomly taken from a depth of 0–15 cm, then air-dried and ground using a rotary trommel. The soil was sieved through a 2 mm mesh for incubation and chemical analysis.

The soil pH was measured using the potentiometric method (Peech, 1965) with a soil-to-solution ratio of 1:2.5 (10 g soil to 25 mL of 0.01 M CaCl2). After shaking the mixture at 180 rpm for 15 minutes using a mechanical shaker, the pH of the suspension was determined using a calibrated digital pH meter (Trans Instruments Professional Benchtop pH meter BP3001, 2019).

The Loss-on-ignition method (Piccolo, 1996) was used for quantifying soil OM. A 5 g sample, dried at 60˚C for 24 hours, was weighed and placed in a crucible. It was then incinerated in a muffle furnace at 300˚C for 1 hour and further heated to 550˚C for 8 hours. After cooling in a desiccator, the sample was weighed again. The weight loss represented the OM content, while the remaining weight corresponded to the ash content.

Total nitrogen (N) content was measured using a CHN analyzer (LECO Elemental Analysis by Combustion CHN628, 2012). A 0.2 g sieved soil sample was weighed, wrapped in aluminum foil, and placed into the analyzer. The analyzer provided the percentage of total nitrogen in the sample.

The total element concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminium (Al), ferum (Fe), sodium (Na), copper (Cu), and zinc (Zn) in the soil were determined using the aqua regia digestion method (Gaudino *et al*., 2007). A 0.5 g soil sample was mixed with 40 mL of aqua regia solution and heated until dry. It was then diluted with 2% HNO3 and filtered through a 0.45 µm hydrophilic filter membrane. The sample was brought to a volume of 100 mL, further diluted by a factor of 30, and analyzed using an ICP-OES analyzer (PerkinElmer Optima 5300DV, 2008). The calculation for nutrient concentration was as follows:

$$\text{ICP value} \times (0.5\ \text{g} / 100\ \text{mL})\ \text{sample} \times \text{dilution factor}$$

2.1 Incubation study

An incubation study was conducted in the Faculty of Sustainable Agriculture (FSA) laboratory using clear polypropylene containers with modified (perforated) lids to ensure proper aeration while preventing contamination. Each container was filled with 300 g of soil, which was moistened to 60% field capacity overnight. The next day, five treatments (T0 to T4) were surface applied with amendment combinations, as outlined in Table 1, marking the start of the experiment (day zero). For each of the treatments, three sets of experimental units were prepared for destructive sampling at 30, 60, and 90 days of incubation. Each set consisted of treatments in triplicate, arranged randomly using a Completely Randomized Design (CRD).
The recommended fertilizer rates in this study were based on maize plant, consists of 120 kg ha^{-1} of N, 60 kg ha^{-1} of P, and 90 kg ha^{-1} of K, corresponding to 260.87 kg ha^{-1} of urea (46% N), 298.95 kg ha^{-1} of triple superphosphate (TSP, 43.64% P), and 177.73 kg ha^{-1} of muriate of potash (MOP, 83.02% K) as per Muhumed et al. (2014). To prevent excessive nutrient supply from amendments, fertilizer rates were reduced to 75% and 50% for determining optimal effectiveness. Dairy farm effluent compost (DFEC) was applied at a 1:4 ratio, as recommended by Maludin et al. (2019), while humic acid (HA) was applied at 25 kg ha^{-1}, based on Daur & Bakhashwain (2013). Treatment details, including scaled fertilizer rates and amendment applications, are provided in Table 1.

Table 1. Rate of fertilizer and applied amendments.

Tr*	Fertilizer (g plant^{-1})			Fertilizer rate (%)	DFEC:Soil	HA (g plant^{-1})
	Urea	TSP	MOP			
T0	4.89	5.61	3.39	100	-	-
T1	3.67	4.21	2.54	75	-	0.47
T2	3.67	4.21	2.54	75	1:4	0.47
T3	2.45	2.81	1.70	50	-	0.47
T4	2.45	2.81	1.70	50	1:4	0.47

Note: *Tr=Treatment.

At the start of the experiment, the initial weight of each container was recorded. Soil moisture was maintained by checking container weights every 5 days and replenishing water losses with distilled water. All experimental units were incubated at room temperature (26˚C) and collected on 30, 60, and 90 days. After collected, soil samples were mixed, air-dried, ground, and analysed for soil pH, organic matter (OM), and total element concentrations (N, P, K, Ca, Mg, Al, Fe, Na, Cu, and Zn).

2.2 Statistical analysis

All the data collected was subjected to one-way analysis of variance (ANOVA) to determine any significant differences between treatment means for all parameters measured. Tukey's HSD test was used for post-hoc analysis at a significance level of 0.05 ($p \leq 0.05$). Statistical analysis was performed using IBM SPSS version 26.

3. Results and Discussion

The results in Table 2, Table 3, and Table 4 showed that organic amendments had no significant effect on soil pH throughout the experiment period (90 days). However, all treatments with amendments significantly increased soil OM content throughout the incubation period compared to the control (T0). As shown in Table 2, all treatments (T1-T4) had significantly higher OM levels than the control at Day 30, showing their contribution to improving subsoil OM as found by Rendana et al. (2022). This increase positively impacts soil health and fertility by enhancing water retention and nutrient cycling, aligning with a study by Magdoff & Van Es (2021). The increase on Day 30 resulted from the organic material in the amendments, which provided an easily accessible carbon source for soil microorganisms. However, by Day 90 (Table 4), soil OM levels decreased by 33%, possibly due to decomposition by indigenous microbes. Despite this decline, the subsoil treated with DFEC maintained higher OM levels than the control (T0), highlighting DFEC significant role in maintaining OM in the soil as stated by Maludin et al. (2019).

At Day 30 (Table 2), all treatments significantly increased subsoil macronutrient concentrations compared to control (T0), with DFEC-treated groups (T2 and T4) showing the highest levels of N, P, K, and Ca, followed by HA-treated groups (T1 and T3). This suggests that DFEC and HA improve nutrient availability through enhanced retention and release mechanisms (Hafez et al., 2023; Maludin et al., 2019). Canellas et al. (2015) support that synergistic effect between HA and DFEC was able to chelate released nutrients in the soil. Although macronutrient concentrations decreased over time as seen in Table 2, Table 3, and Table 4, the macronutrient pattern observed across treatments on Day 30, 60, and 90 were consistent, demonstrating the sustained impact of amendments.

The Al and Fe concentrations showed fluctuating patterns during the experiment, increasing significantly between Days 30 and 60 (Table 2 and 3) before decreasing at Day 90 (Table 4). The initial rise in Al concentration may be attributed to desorption triggered by soil pH changes or microbial activity, while its subsequent decline suggests immobilization or precipitation due to microbial processes (Zhang et al., 2023). It also may be linked to interactions with the subsoil matrix, where Al adsorbs onto soil particles and its mobility is influenced by pH (Li et al., 2022). The increase in Fe concentration in T3, T4, and T8 could be linked to redox reactions, as Fe solubility depends on oxidation states, potentially enhanced by amendments or microbial activity (Colombo et al., 2013; O'Loughlin et al., 2021). Fe mobility may also have been influenced by complexation with organic ligands, aided by degradable organic matter in certain treatments.

The addition of DFEC elevated Na levels in T2 and T4 although these gradually declined over time as found by Acharya et al. (2019). The elevated Na concentration in treatments with DFEC was likely due to OM decomposition, which released Na ions into the subsoil. Over time, this concentration decreased as decomposition slowed, with Na being adsorbed onto soil particles or may assimilated by microbes as stated by Li-Xian et al., (2007). Copper initially

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found in trace amounts and highest in T0 (control), significantly declined across treatments, nearly reaching zero by Day 90. Regardless of amendments application, Zn which was present in trace amounts showed no significant changes. This was likely due to its low mobility and strong adsorption to soil particles (Kaur et al., 2024). These trends suggest that OM addition and microbial activity influenced the dynamics of these metals (Poveda & Eugui, 2022), with Cu potentially immobilized by microbial processes (Cornu et al., 2017), while Zn behavior remained stable due to its inherent properties.

Overall, the prominent effect of DFEC compared to treatments without it could be attributed to differences in decomposition rates, inherent chemical composition, and unique chemical properties. The Al and Fe fluctuations alongside Na, showed the complex interactions between amendments, soil chemistry and perhaps microbial activity. Meanwhile, Cu and Zn concentrations were influenced by microbial immobilization and limited mobility, reflecting a complex metal dynamic in amended soils. Despite declines in nutrient levels over time, the sustained patterns highlight the long-term impact of DFEC and HA in enriching subsoils.

Table 2. Mean values soil pH, soil OM, and total elements content at 30 days of incubation.

Day 30					
Tr*	**T0**	**T1**	**T2**	**T3**	**T4**
pH	5.35±0.12bc	5.23±0.18c	5.56±0.15a	5.32±0.16bc	5.50±0.02ab
OM (%)	1.24±0.14c	1.50±0.08ab	2.16±0.22a	1.56±0.01b	2.23±0.10a
N (%)	0.1204±0.0005d	0.1266±0.0005c	0.1682±0.0023b	0.1262±0.0009c	0.1763±0.0026a
P (ppm)	1.50±0.39d	3.23±0.25b	17.25±0.51a	2.65±0.13c	16.97±0.44a
K (ppm)	24.06±0.47b	23.91±0.83b	36.41±0.66a	23.94±0.29b	35.75±1.14a
Ca (ppm)	37.58±0.60cd	38.61±0.64c	57.39±0.89b	35.78±0.25d	59.09±0.98a
Mg (ppm)	68.21±1.20a	68.11±1.71a	65.34±0.77bc	65.92±0.55b	64.31±1.15c
Al (ppm)	109.11±1.74d	143.37±4.17a	118.44±0.93c	124.68±1.42b	115.11±2.17cd
Fe (ppm)	194.07±3.65e	286.37±5.43a	251.01±2.16b	222.88±2.10d	231.82±2.37c
Na (ppm)	3.42±0.11c	3.17±0.13cd	8.32±0.13a	2.98±0.12d	8.02±0.12b
Cu (ppm)	0.10±0.03a	0.05±0.01b	0.03±0.02c	0.02±0.02d	0.02±0.01cd
Zn (ppm)	0.82±0.04a	0.77±0.01b	0.71±0.03cd	0.66±0.05d	0.73±0.01c

Note: T0=Control (100% FR*); T1=HA (75% FR*); T2=HA + DFEC (75% FR*); T3=HA (50% FR*); T4=HA + DFEC (50% FR*); *Tr=Treatment; FR=Fertilizer rate; Means denoted with different letters indicate significant differences as determined by Tukey's Test at a significance level of $p \leq 0.05$.

Table 3. Mean values soil pH, soil OM, and total elements content at 60 days of incubation.

Day 60					
Tr*	**T0**	**T1**	**T2**	**T3**	**T4**
pH	5.27±0.28ab	5.20±0.22b	5.34±0.21ab	5.02±0.12c	5.48±0.20a
OM (%)	1.03±0.17c	1.42±0.12b	2.11±0.10a	1.36±0.11b	2.13±0.16a
N (%)	0.1202±0.0011d	0.1269±0.0013c	0.1719±0.0023b	0.1246±0.0002cd	0.1753±0.0026a
P (ppm)	2.16±0.33cd	2.02±0.39d	15.93±0.35a	2.71±0.61c	14.62±0.41b
K (ppm)	25.52±0.47cd	23.21±0.35d	38.75±0.93b	26.28±0.69c	41.00±1.21a
Ca (ppm)	37.62±0.04c	38.12±0.18c	61.50±0.91a	41.43±0.42b	61.97±1.19a
Mg (ppm)	66.27±0.79c	66.10±0.34c	66.40±1.05c	71.95±1.33a	69.69±1.49b
Al (ppm)	125.96±1.99ab	114.45±1.12d	118.67±1.81c	127.53±2.94a	128.40±2.80a
Fe (ppm)	225.41±1.46bc	204.64±0.95d	244.61±3.05a	217.52±2.52c	242.33±4.22ab
Na (ppm)	3.44±0.02b	3.17±0.16bc	8.30±0.14a	2.86±0.04c	8.32±0.28a
Cu (ppm)	0.02±0.01a	ND*	ND*	ND*	0.02±0.01a
Zn (ppm)	0.63±0.02b	0.61±0.02bc	0.68±0.01a	0.61±0.01bc	0.67±0.01a

Note: T0=Control (100% FR*); T1=HA (75% FR*); T2=HA + DFEC (75% FR*); T3=HA (50% FR*); T4=HA + DFEC (50% FR*); *Tr=Treatment; FR=Fertilizer rate; ND=Not detected; Means denoted with different letters indicate significant differences as determined by Tukey's Test at a significance level of $p \leq 0.05$.

Table 4. Mean values soil pH, soil OM, and total elements content at 90 days of incubation.

	Day 90				
Tr*	**T0**	**T1**	**T2**	**T3**	**T4**
pH	5.35±0.22ab	5.09±0.16b	5.21±0.16b	5.26±0.20ab	5.51±0.10a
OM (%)	0.89±0.08c	1.08±0.06b	1.82±0.19a	1.16±0.02b	1.69±0.04a
N (%)	0.1191±0.0033b	0.1240±0.0003b	0.1684±0.0005a	0.1233±0.0003b	0.1723±0.0011a
P (ppm)	1.63±0.42c	2.16±0.39c	15.40±0.27b	2.22±0.63c	16.67±0.75a
K (ppm)	29.18±0.78b	25.24±0.67c	39.08±0.73a	25.61±0.56c	38.32±1.00a
Ca (ppm)	39.98±0.65b	37.52±0.45c	60.06±0.64a	36.97±0.33c	62.04±0.99a
Mg (ppm)	74.08±1.90a	67.26±1.38b	65.55±0.90b	66.04±1.22b	66.93±1.16b
Al (ppm)	122.02±3.02bc	128.14±2.92ab	123.47±1.47bc	131.87±2.54a	115.85±2.30c
Fe (ppm)	190.06±3.55c	233.14±3.74b	233.05±1.21b	235.11±2.96ab	236.67±2.66a
Na (ppm)	3.37±0.14b	2.58±0.07c	7.55±0.06a	2.65±0.03c	7.78±0.23a
Cu (ppm)	0.01±0.01a	ND*	ND*	ND*	ND*
Zn (ppm)	0.69±0.02a	0.60±0.01c	0.64±0.01b	0.59±0.03c	0.66±0.03ab

Note: T0=Control (100% FR*); T1=HA (75% FR*); T2=HA + DFEC (75% FR*); T3=HA (50% FR*); T4=HA + DFEC (50% FR*); *Tr=Treatment; FR=Fertilizer rate; ND=Not detected; Means denoted with different letters indicate significant differences as determined by Tukey's Test at a significance level of $p \leq 0.05$.

4. Conclusion

This study highlights the potential of DFEC and HA as effective organic amendments for subsoil rejuvenation in sustainable farming. Treatment 4 (DFEC and HA with a 50% reduction in fertilizer rates) was the best combination, highlighting the role of macronutrient improvement in subsoil restoration. The overall enrichment of subsoil organic matter (OM) and nutrient concentrations shows the benefits of incorporating these amendments, which appear to enhance nutrient retention and availability. As a key factors for supporting sustainable agricultural practices, these findings provide insights into effective strategies for subsoil rehabilitation and sustainable nutrient management, contributing to both local and global efforts to overcome soil degradation. This investigation may contribute to advancing sustainable agricultural practices and developing innovative solutions for soil management challenges. Further research including pot and field tests is necessary to understand these mechanisms fully, particularly in the presence of crops, to establish robust soil amendment strategies for sustainable agriculture.

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References

Acharya, P., Ghimire, R., & Cho, Y. (2019). Linking soil health to sustainable crop production: dairy compost effects on soil properties and sorghum biomass. Sustainability, 11(13), 3552. https://doi.org/10.3390/su11133552

Ampong, K., Thilakaranthna, M. S., & Gorim, L. Y. (2022). Understanding the role of humic acids on crop performance and soil health. Frontiers in Agronomy, 4, 1-11, 848621. https://doi.org/10.3389/fagro.2022.848621

Bhatt, P., & Singh, V. (2022). Effect of humic acid on soil properties and crop production– A review. The Indian Journal of Agricultural Sciences, 92(12), 1423-1430. https://doi.org/10.56093/ijas.v92i12.124948

Canellas, L. P., Olivares, F. L., Aguiar, N. O., Jones, D. L., Nebbioso, A., Mazzei, P., & Piccolo, A. (2015). Humic and fulvic acids as biostimulants in horticulture. Scientia Horticulturae, 196, 15–27. https://doi.org/10.1016/j.scienta.2015.09.013

Colombo, C., Palumbo, G., He, J.-Z., Pinton, R., & Cesco, S. (2013). Review on iron availability in soil: Interaction of Fe minerals, plants, and microbes. Journal of Soils and Sediments, 14(3), 538-548. https://doi.org/10.1007/s11368-013-0814-z

Cornu, J.-Y., Huguenot, D., Jézéquel, K., Lollier, M., & Lebeau, T. (2017). Bioremediation of copper-contaminated soils by bacteria. World Journal of Microbiology and Biotechnology, 33(2), 26. https://doi.org/10.1007/s11274-016-2191-4

Daur, I., & Bakhashwain, A. (2013). Effect of humic acid on growth and quality of maize fodder production. Pakistan Journal of Botany, 45, 21–25.

Faridah, M., Zawawi, N. Z., & Liza Nuriati L. K. C. (2022, October 18). Soil fertility management for sustainable plant production in Malaysia. FFTC Agricultural Policy Platform. https://ap.fftc.org.tw/article/3178

Gaudino, S., Galas, C., Belli, M., Barbizzi, S., Zorzi, P., Jaćimović, R., Jeran, Z., Pati, A., Sansone, U. (2007). The role of different soil sample digestion methods on trace elements analysis: A comparison of ICP-MS and INAA measurement results. *Accreditation and Quality Assurance, 12*, 84–93. https://doi.org/10.1007/s00769-006-0238-1

Gupta, S., Kulkarni, M. G., White, J. F., Stirk, W. A., Papenfus, H. B., Doležal, K., Ördög, V., Norrie, J., Critchley, A. T., & Van Staden, J. (2021). Categories of various plant biostimulants – mode of application and shelf-life. In S. Gupta & J. Van Staden (Eds.), Biostimulants for Crops from Seed Germination to Plant Development (pp. 1–60). Elsevier. https://doi.org/10.1016/B978-0-12-823048-0.00018-6

Hafez, M., El-Nile, A., Hassan, M., Zeitar, E., Mohammed, S., Abdallah, A., Zohir, W., Popov, A., Minkina, T., & Rashad, M. (2023). Humic substances and their potential to enhance soil, plants, and animals' productivity: a new concept for sustainable agriculture. In: Gorawala P, & Mandhatri S. (Eds.), Agricultural Research Updates (Vol. 44, p. 189). Nova Publisher.

Kaur, H., Srivastava, S., Goyal, N., & Walia, S. (2024). Behavior of zinc in soils and recent advances on strategies for ameliorating zinc phyto-toxicity. Environmental and Experimental Botany, 220, 105676. https://doi.org/10.1016/j.envexpbot.2024.105676

Kumar, P., Bagri, J., Kumar Yadav, K., & Yadav, L. (2024). Soil erosion: causes and consequences. In Kumar, P., Bagri, J. P., Kumar Yadav, K., Yadav, L., & Kumar, D.(Eds.), Guardians of the Earth (pp. 13–36). A K International Publication.

Li, Q., Wang, Y., Li, Y., Li, L., Tang, M., Hu, W., Chen, L., & Ai, S. (2022). Speciation of heavy metals in soils and their immobilization at micro-scale interfaces among diverse soil components. Science of The Total Environment, 825, 153862. https://doi.org/10.1016/j.scitotenv.2022.153862

Li-Xian, Y., Guo-Liang, L., Shi-Hua, T., Gavin, S., & Zhao-Huan, H. (2007). Salinity of animal manure and potential risk of secondary soil salinization through successive manure application. Science of The Total Environment, 383, 106–114. https://doi.org/10.1016/j.scitotenv.2007.05.027

Magdoff, F., & Van Es, H. (2021). Building Soils for Better Crops: Ecological Management for Healthy Soils (4th ed.). Sustainable Agriculture Research and Education (SARE).

Maludin, A. J., Aisar, N., Silip, J., Fook, Y., & Gobilik, J. (2019). Effects of dairy farm effluent compost on growth and yield of pak choy (*Brassica rapa* L.) in pot system. Transaction on Science and Technology, 6, 272–282.

Muhumed, M., Shamshuddin, J., Teh, C., Edaroyati, P., Megat Wahab, P., & Panhwar, Q. (2014). Influence of NPK fertilizer rates and irrigation frequencies on the biomass and yield components of sweet corn (*Zea mays* L.). Journal of Food Agriculture and Environment, 12, 1308–1313.

O'Loughlin, E. J., Boyanov, M. I., Gorski, C. A., Scherer, M. M., & Kemner, K. M. (2021). Effects of Fe(III) oxide mineralogy and phosphate on Fe(II) secondary mineral formation during microbial iron reduction. Minerals, 11(2), 149. https://doi.org/10.3390/min11020149

Pandian, K., Mustaffa, M. R. A. F., Mahalingam, G., Paramasivam, A., John Prince, A., Gajendiren, M., Rafiqi Mohammad, A. R., & Varanasi, S. T. (2024). Synergistic conservation approaches for nurturing soil, food security and human health towards sustainable development goals. Journal of Hazardous Materials Advances, 16, 100479. https://doi.org/10.1016/j.hazadv.2024.100479

Peech, M. (1965). Hydrogen-Ion Activity. In C. A. Black, D. D. Evans, L. E. Ensminger, J. L. White, F. E. Clark, & R. C. Dinauer (Eds.), Methods of Soil Analysis - Part 2 (pp. 914–926). American Society of Agronomy. https://doi.org/10.2134/agronmonogr9.2.c9

Piccolo, A. (1996). Humus and soil conservation. In A. Piccolo (Ed.), Humic Substances in Terrestrial Ecosystems (pp. 225–264). Elseiver.

Poveda, J., & Eugui, D. (2022). Combined use of *Trichoderma* and beneficial bacteria (mainly *Bacillus* and *Pseudomonas*): Development of microbial synergistic bio-inoculants in sustainable agriculture. Biological Control, 176, 105100. https://doi.org/10.1016/j.biocontrol.2022.105100

Rendana, M., Idris, W. M. R., Abd Rahim, S., Rahman, Z. A., & Lihan, T. (2022). Effects of organic amendment on heavy metal and macronutrient contents in paddy soil. Sains Malaysiana, 51(2), 379–388. https://doi.org/10.17576/jsm-2022-5102-05

Smith, J. L., & Collins, H. P. (2007). Management of organisms and their processes in soils. In E. A. Paul (Ed.), Soil Microbiology, Ecology and Biochemistry (pp. 471–502). Elsevier. https://doi.org/10.1016/B978-0-08-047514-1.50021-4

Zhang, W., Zhang, H., Xu, R., Qin, H., Liu, H., & Zhao, K. (2023). Heavy metal bioremediation using microbially induced carbonate precipitation: Key factors and enhancement strategies. Frontiers in Microbiology, 14, Article 1116970. https://doi.org/10.3389/fmicb.2023.1116970

Zhu, X. F., & Shen, R. F. (2024). Towards sustainable use of acidic soils: Deciphering aluminum-resistant mechanisms in plants. Fundamental Research, 4(6), 1533–1541. https://doi.org/10.1016/j.fmre.2023.03.004