International Journal of Science, Engineering & Environmental Technology (IJOSEET), 17(17): 84-97, 2025
ISSN 0794-9650

www.repcomseet.org

Integrated Nutrient Dynamics of Vermicompost, Vermitea, and NPK Fertilizer: Implications for Soil Fertility and Sustainable Agriculture

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Abstract: *The accelerating rate of urbanization and industrialization has intensified the global challenge of managing biodegradable solid waste, particularly kitchen residues, which pose severe environmental and public health risks when improperly disposed of. This study investigated the potential of Eisenia fetida-mediated vermicomposting as a sustainable bio-conversion strategy for transforming kitchen waste into nutrient-rich biofertilizers (vermicompost and vermitea) and compared their nutrient profiles with conventional NPK fertilizer and native soil. The experiment was conducted under controlled bin-based vermicomposting conditions using mixed green and brown kitchen wastes, humus soil, and standardized bedding materials. Physicochemical analyses of the harvested vermicompost, vermitea, NPK fertilizer, and soil samples were performed to determine key macronutrients; nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na).*

Results revealed substantial nutrient variability among the treatments. The combined vermicompost + vermitea formulation exhibited the highest concentrations of calcium (353.37 mg/L) and magnesium (52.81 mg/L), signifying enhanced mineralization and microbial synergism, while NPK fertilizer recorded the highest potassium (800.01 mg/L), phosphorus (686.36 mg/L), and nitrogen (14.21%) contents. Although inorganic fertilizer provided immediate nutrient availability, the organic formulations demonstrated superior contributions to secondary nutrient enrichment, pH balance, and potential for improving soil biological activity and cation exchange capacity. The findings indicated the complementary role of biofertilizers in maintaining soil fertility, mitigating salinity risks, and enhancing long-term soil health within an integrated nutrient management (INM) framework.

It is recommended that farmers adopt a combined application of organic (vermicompost + vermitea) and inorganic (NPK) fertilizers to achieve balanced nutrient availability and ecological sustainability. Field-based validation and long-term trials are further advised to optimize nutrient-use efficiency and microbial resilience under diverse agroecological conditions. This study reaffirms vermitechnology as a viable circular-economy pathway for converting organic waste into high-value biofertilizers, thereby promoting regenerative and climate-smart agricultural systems.

Keywords: *Biofertilizer, Integrated Nutrient Management, NPK fertilizer, Soil fertility Vermicompost, Vermitea*

1.0. Introduction

Biofertilizers are natural fertilizers that contain living microorganisms which, when applied to soil or plant surfaces, promote growth by increasing the supply or availability of essential nutrients such as nitrogen, phosphorus, and other minerals to the host plant. Unlike chemical fertilizers that supply nutrients directly, biofertilizers enhance soil fertility through biological processes such as nitrogen fixation, phosphate solubilization, and organic matter decomposition (Mahmud *et al.,* 2021). They play a significant role in sustainable agriculture by improving soil health, enhancing crop yield, and reducing environmental pollution associated with synthetic fertilizers.

The rapid pace of urbanization, industrialization, and economic expansion has led to a dramatic increase in the generation of solid waste globally. Managing this ever-growing volume of waste has become one of the most pressing ecological and technical challenges of the 21st century (Zhang *et al.,* 2023). Global municipal solid waste (MSW) generation increased from 635 million tonnes to nearly 2000 million tonnes in 2015 and is projected to reach 3,500 million tonnes by 2050. Organic waste remains the largest component, accounting for 40–70% of MSW, especially in developing countries (Chen *et al.,* 2020). This projection means that there is an urgent need for sustainable and innovative waste management practices to maintain a healthy and clean environment (Kumar *et al.*, 2023).

Improper waste disposal poses serious environmental and public health threats. Contamination of water, soil, and air from unmanaged waste can result in disease transmission and environmental degradation (Akmal and Jamil, 2021). Hazardous waste and unsafe treatment practices such as open burning can directly harm workers and residents of nearby communities (Krecl *et al.*, 2021). Similarly, poor waste collection systems and indiscriminate dumping into rivers, seas, and lagoons contribute to marine pollution, block drainage channels, and increase the risk of urban flooding.

Specifically, accumulation of organic waste materials, including agricultural residues, kitchen scraps, and food remnants is on the increase globally. These wastes often emit offensive odours and contribute to environmental pollution when improperly disposed of. The challenge of managing these biodegradable wastes necessitates the adoption of an efficient, affordable, and environmentally sustainable method to convert them into valuable products rather than pollutants (Chen *et al.*, 2020).

The conversion of organic solid waste into biofertilizers presents an eco-friendly and economically viable approach to address both agricultural and environmental challenges. Through composting, vermicomposting, and microbial inoculation techniques, organic wastes can be transformed into nutrient-rich biofertilizers that not only reduce waste volume but also improve soil fertility and promote sustainable crop production. Hence, integrating biofertilizer production into solid waste management systems offers a dual benefit, mitigating waste accumulation and enhancing agricultural productivity.

Vermi-technology (commonly referred to as vermicomposting) has emerged as a promising, eco-friendly alternative within the framework of integrated solid waste management. Vermicomposting involves the stabilization and biodegradation of organic matter through the synergistic activity of earthworms and soil microorganisms (Chen, 2023). Earthworms play a pivotal role in this process by fragmenting organic material, enhancing microbial activity, and promoting biochemical degradation (Liao, 2024).

Vermicomposting transforms organic waste into a homogeneous, humus-like product known as vermicompost (Kaur *et al.*, 2020). This bio-fertilizer is an odourless, nutrient-rich organic material comprising the fecal matter of earthworms and decomposed organic waste. It contains essential macronutrients (N, P, K) and several micronutrients beneficial for soil fertility and plant growth (Bhardwaj *et al.,* 2014). Research has demonstrated that various earthworm species can effectively convert diverse organic wastes into vermicompost, reducing dependency on chemical fertilizers and contributing to sustainable agricultural production (Alam *et al.*, 2007). Moreover, the vermicomposting process is significantly faster than conventional composting, with waste bioconversion occurring two to five times more rapidly. The primary aim of this study is to produce a bio-fertilizer through the process of vermicomposting, utilizing earthworms for the conversion of biodegradable kitchen waste into nutrient-rich compost.

2.0. Methodology

2.1. Study site and Materials

The research was conducted at the Federal Polytechnic, Ede (North Campus), Osun State, Nigeria. Approximately 100 g of humus soil was collected from the study site and preserved for subsequent analysis. In addition, 100 g of NPK fertilizer was obtained from local farmers to serve as a standard reference for comparison with the vermicompost and vermitea produced during the study. For the production of vermicompost and vermitea, various biodegradable organic wastes were sourced primarily from kitchen residues. The green wastes included fresh plant materials such as water leaf, banana leaves, spinach, and amaranthus, while the brown wastes comprised banana peels, plantain peels, yam peels, potato peels, and eggshells. Bedding materials such as shredded newspapers and coconut coir were used to provide aeration and a conducive environment for the earthworms. Humus soil was incorporated into the setup to introduce beneficial microorganisms that enhance the decomposition process. The earthworm species *Eisenia fetida* was selected for its proven efficiency in the degradation of organic wastes. All materials were assembled within a vermicomposting bin, which served as the containment unit for the entire process. This follows that standard procedure as stated by (Ramnarain *et al.*, 2019; Dume *et al.*, 2023)

2.2. Vermicomposting Procedure

A bin-based vermicomposting system was selected as the most suitable method based on space availability and experimental requirements. The vermicomposting bin as shown in fig 2.1, measuring 60 cm in length, 45 cm in width, and 30 cm in depth, was designed to ensure adequate aeration, drainage, and insulation, thereby maintaining optimal environmental conditions for earthworm activity. The prepared bedding materials were placed at the base of the bin, followed by layers of green and brown kitchen wastes. A thin layer of humus soil was added to introduce microbial flora, after which the earthworms (*Eisenia fetida*) were introduced into the system. The setup was maintained under favourable conditions, including proper moisture, pH, and temperature control, to enhance the decomposition process. Regular monitoring was conducted to ensure the well-being of the worms and to maintain the balance between green and brown materials. Upon completion of the composting period, the vermicompost and vermitea were harvested for further analysis.

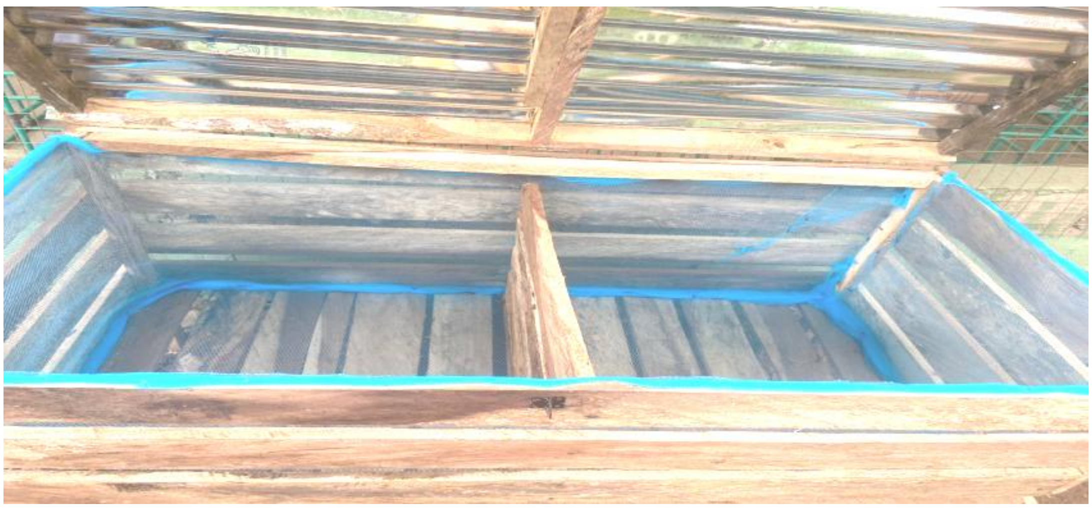

Fig 2.1: Vermicompost Bin

2.3. Preparation of Bedding Materials

The bedding materials for the vermicomposting setup as shown in fig 2.2 consisted of newspapers, shredded papers, and coconut coir, which served both as a habitat and a supplementary food source for the earthworms. Newspapers were first laid at the bottom of the bin to create a base layer, followed by an even spread of shredded papers and coconut coir to provide aeration and structural support. The entire bedding mixture was then moistened to achieve a damp, sponge-like consistency, ensuring optimal conditions for earthworm activity without creating waterlogged conditions that could hinder aeration or worm mobility.

Fig 2.2: Bedding Preparations

2.4. Introduction of Organic Wastes to the bin

The vermicomposting bin was subsequently stocked with equal proportions of green and brown kitchen wastes to ensure a balanced carbon-to-nitrogen ratio essential for effective decomposition (fig 2.3). The green wastes included fresh vegetable materials such as water leaf, banana leaves, spinach, and *amaranthus*, while the brown wastes comprised banana peels, plantain peels, yam peels, potato peels, and eggshells. To maintain hygienic conditions and prevent pest infestation or foul odors, meat, dairy products, oily residues, and pet wastes were deliberately excluded from the setup. The total weight of organic waste introduced into the bin was 10.705 kg (10,705 g).

Fig 2.3: Stocking the bin with green and brown wastes

2.5. Introducing soil and earthworm to the waste

After preparing the bedding and layering the organic wastes, humus soil was added intermittently between the layers to enhance nutrient availability and moisture retention, thereby creating a favorable microenvironment for earthworm activity and facilitating efficient waste decomposition. The earthworm species *Elsenia fetida*, known for its high reproductive rate and adaptability to composting conditions, was selected for the study. A total of 572 earthworms were introduced evenly across the bin to ensure uniform distribution and effective biodegradation of the organic materials (Fig 2.4).

Fig 2.4: Addition of soil and introduction of earthworms to the waste

2.6. Harvesting the Vermicompost and vermitea

After about three months of active decomposition, the organic wastes were completely converted into a dark, nutrient-rich, humus-like material referred to as vermicompost. To recover the compost while retaining the earthworm population, a migration technique was adopted. The matured vermicompost was gently moved to one side of the bin, and fresh bedding and feed materials were added to the other side. This encouraged the earthworms to naturally migrate toward the new food source, leaving the finished compost largely free of worms. The harvested vermicompost was then collected and stored in a dry, covered container to maintain its nutrient integrity for subsequent use or laboratory analysis. Additionally, the liquid by-product generated from earthworm activity, known as vermitea, was collected weekly from the drainage outlet ofthe bin and stored in clean containers for later evaluation and application.

Fig 2.5: Waste turning to a compost

2.7. Physicochemical analysis:

The physicochemical analysis of the samples; vermicompost, vermitea, NPK fertilizer, and soil from the study site was conducted to determine their contents of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) (Moubareck *et al.*, 2023). This analysis provided a comparative basis for evaluating the nutrient composition and fertilizing potential of the biofertilizers (vermicompost and vermitea) relative to the chemical fertilizer (NPK), while the soil sample served as a blank control for the study.

3.0. Results and Discussion

3.1 Results

Calcium (Ca)

Fig 3.1 shows the calcium concentrations (Ca mg/L) in the various samples analyzed: vermicompost, soil, vermitea, NPK fertilizer, and a mixture of vermicompost with vermitea. The calcium level was highest in the vermicompost + vermitea sample (353.37 mg/L), and lowest in NPK 19.67 mg/L.

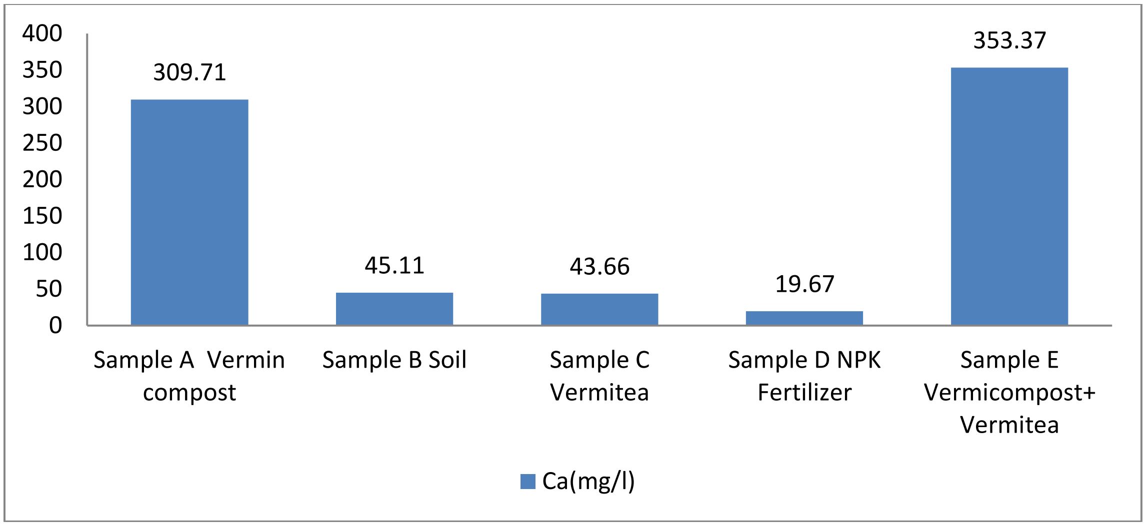

Fig 3.1 Calcium level in the samples

Magnessium (Mg).

Fig 3.2 illustrates the magnesium (Mg) concentrations in the various samples analyzed. Among the samples, the highest magnesium content was recorded in the vermicompost + vermitea sample (52.81 mg/L), while the lowest was observed in the vermicompost sample (15.01 mg/L).

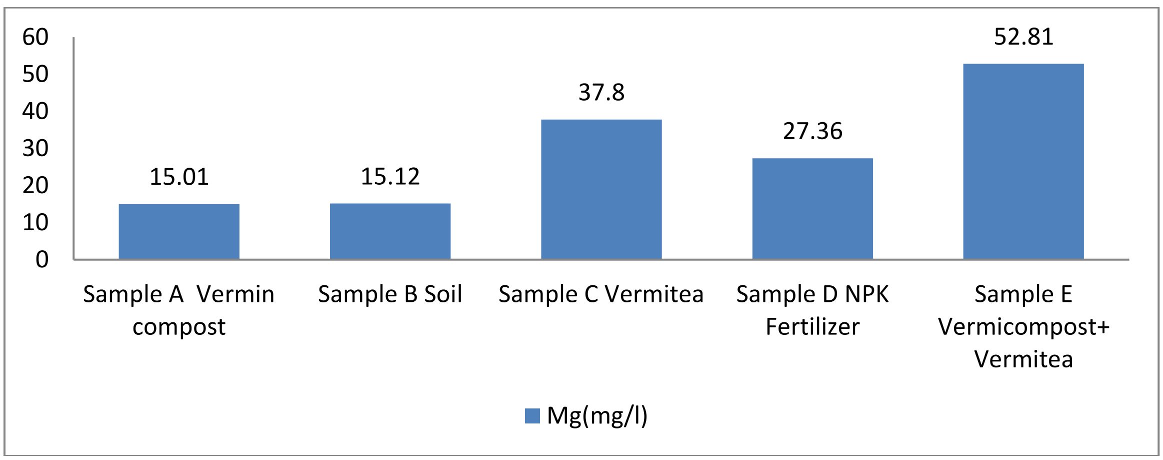

Fig 3.2 Magnesium level in the samples

Fig 3.3 illustrates the Potassium (K) concentrations in the various samples analyzed. Among the samples, the highest magnesium content was recorded in the NPK sample (800.01 mg/L), while the lowest was observed in the vermicompost sample (8.32 mg/L).

Potassium (K)

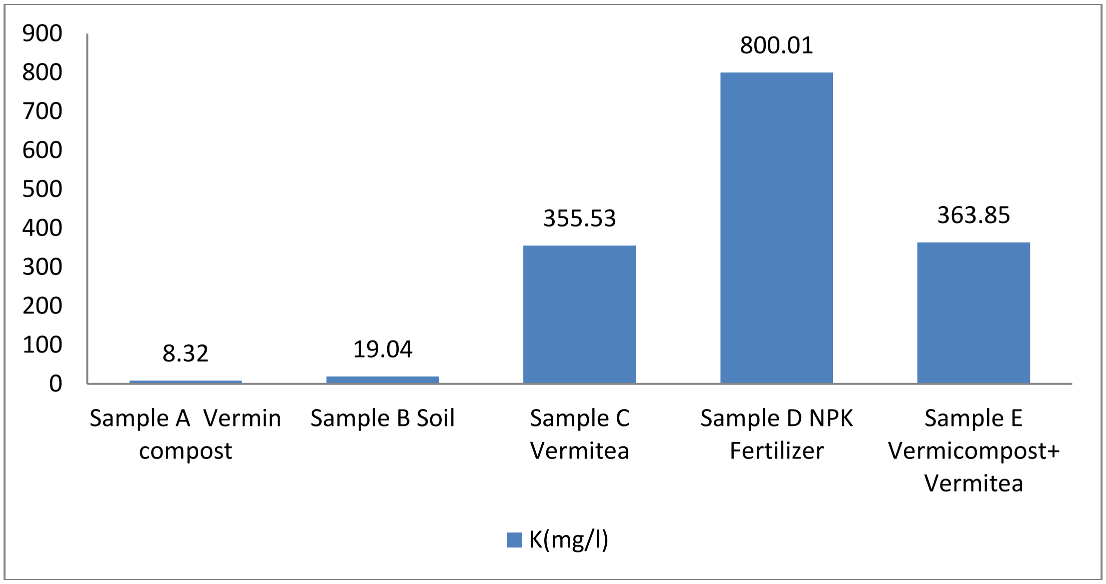

Fig 3.3 Potassium level in the samples

Fig 3.4 illustrates the Sodium (Na) concentrations in the various samples analyzed. Among the samples, the highest magnesium content was recorded in the Vermicompost + vermitea sample (195.19 mg/L), while the lowest was observed in the vermicompost sample (20.13 mg/L).

Sodium (Na).

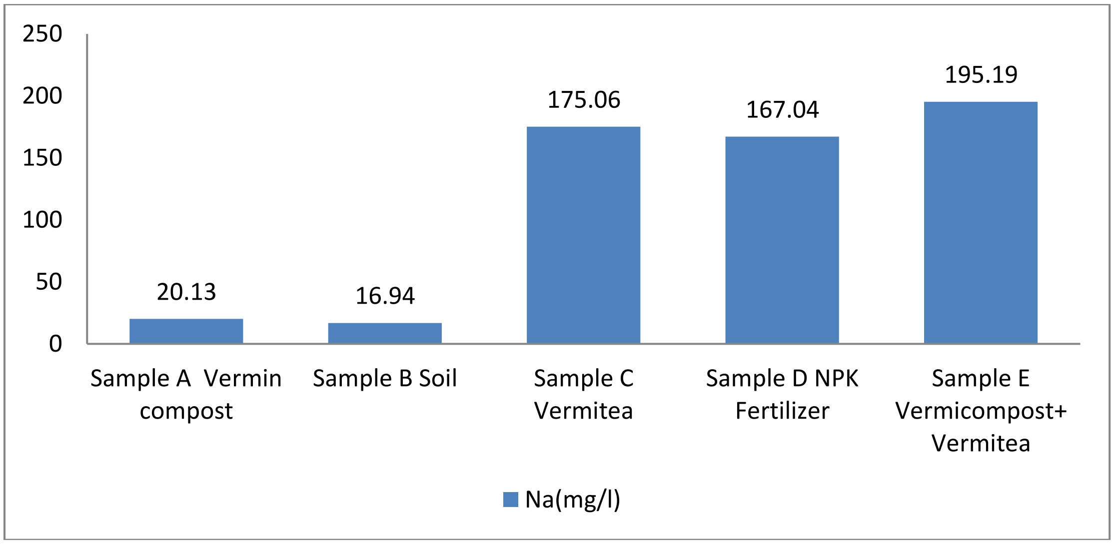

Fig 3.4 Sodium level in the samples

Fig 3.5 illustrates the Phosphorus (P) concentrations in the various samples analyzed. Among the samples, the highest magnesium content was recorded in the NPK sample (686.356 mg/L), while the lowest was observed in the vermicompost sample (159.63 mg/L).

Phosphorus (P)

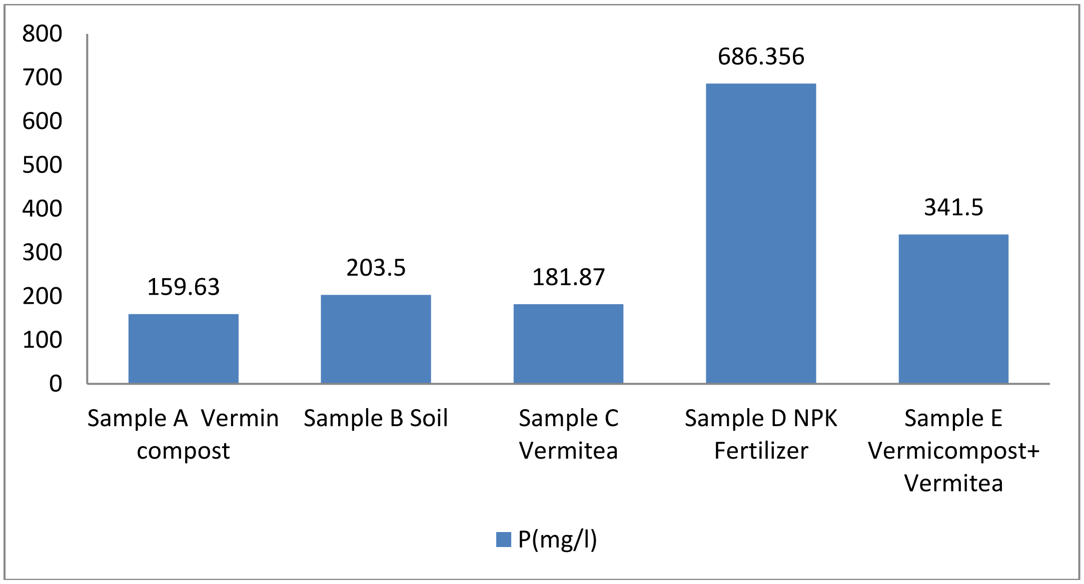

Fig 3.5: Phosphorus level in the samples

Nitrogen (N)

Figure 3.6 illustrates the Nitrogen (N) concentrations in the various samples analyzed. Among the samples, the highest magnesium content was recorded in the NPK sample (14.2%), while the lowest was observed in the vermitea sample (0.56%).

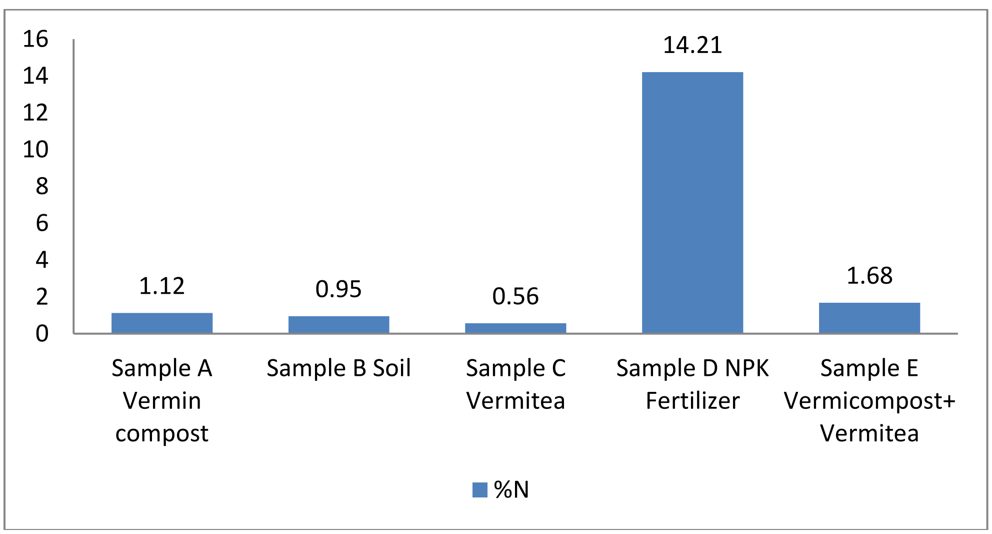

Fig 3.6 Nitrogen level in the samples

Fig 3.6 presents a summary table showing the concentrations of notable elements detected in each of the analyzed samples. The table provides a comparative overview of key macro- and micronutrients such as calcium, magnesium, potassium, sodium, and phosphorus across the different treatments

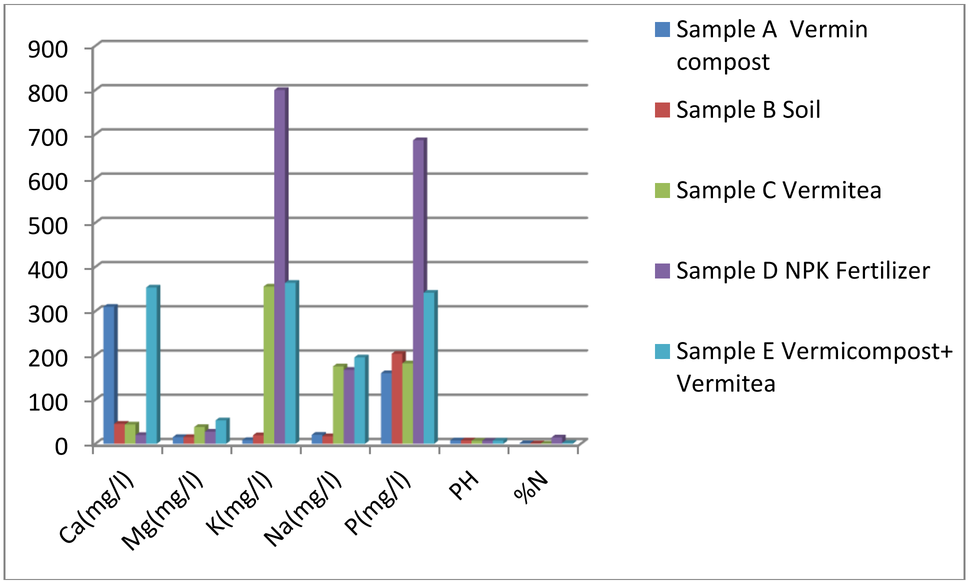

Fig 3.6: Summary representation of notable elements in each of the sample analyzed

Hydrogen Ion Concentration (pH) of the Samples

The bar chart illustrates the pH values of five different samples subjected to various soil amendments. Sample A (Vermicompost) and Sample B (Soil) recorded the highest pH values of 7.43 and 7.45, respectively, indicating slightly alkaline conditions. In contrast, Sample C (Vermitea) and Sample D (NPK Fertilizer) showed lower pH values of 6.69 and 6.77, reflecting more acidic tendencies. Sample E (Vermicompost + Vermitea) exhibited a moderate pH value of 7.06, suggesting a balanced condition between acidity and alkalinity.

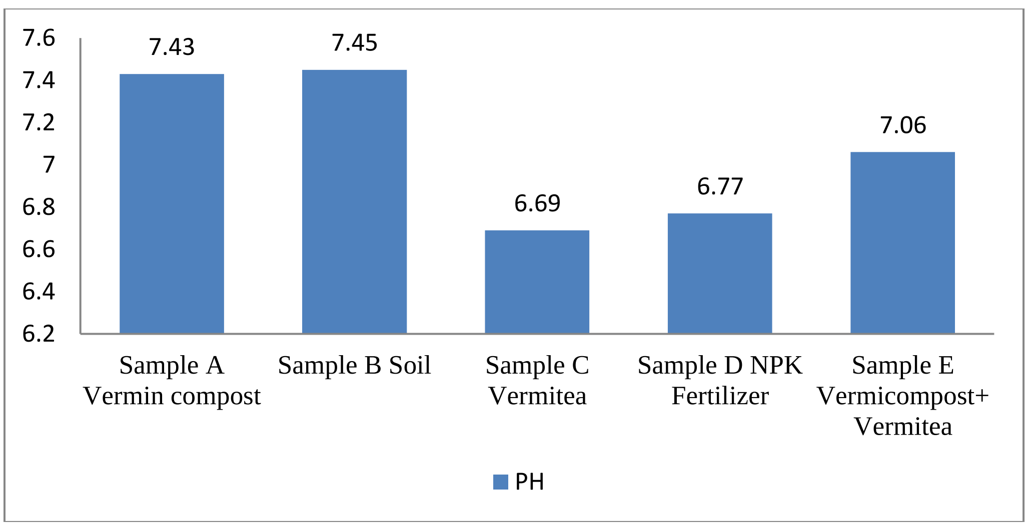

Fig 3.7: Variation in pH of Different Soil Treatment Samples

3.2 Discussions

The comparative evaluation of nutrient composition across the analyzed samples: vermicompost, vermitea, NPK fertilizer, soil, and the combined vermicompost + vermitea formulation, reveals a consistent pattern of significant variation in the availability and enrichment potential of key macroelements, namely calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), phosphorus (P), and nitrogen (N). Collectively, the results show the distinct nutrient dynamics of organic versus inorganic fertilizer systems and give emphasis to the agronomic and ecological implications of their integration.

4.1.1 Nutrient Synergy and Organic Enrichment

The combined application of vermicompost and vermitea (Sample E) demonstrated superior enrichment of secondary macronutrients, particularly calcium (353.37 mg/L) and magnesium (52.81 mg/L), compared to their individual applications. This observation highlights a synergistic mineralization effect driven by the interaction between solid organic matter and microbially active aqueous extracts. The diverse microbial consortia and enzymatic activities inherent in vermitea likely accelerate the solubilization and mobilization of mineral elements from the compost matrix, corroborating earlier reports by Oviedo-Ocaña *et al*. (2022) and Mohamed *et al*. (2022). Such nutrient synergy enhances nutrient cycling, soil aggregation, and enzymatic activation processes that are essential for restoring and sustaining soil fertility in organic production systems.

In contrast, NPK fertilizer exhibited the highest concentrations of potassium (800.01 mg/L), phosphorus, and nitrogen (14.21%), reflecting its high solubility and immediate nutrient availability. However, this nutrient delivery mechanism lacks the organic carbon framework necessary for maintaining long-term soil health. Biofertilizer treatments, on the other hand, showed a slower but more sustained nutrient-release profile that supports microbial proliferation and nutrient retention within the rhizosphere. This finding aligns with the observations of Dal Cortivo *et al*. (2020) and Wichaphian *et al*. (2025), who emphasized the agroecological benefits of slow-release organic inputs in enhancing nutrient-use efficiency and reducing leaching losses.

4.1.2 Balancing Ionic Interactions and Soil Health

The interplay among cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and anions (PO_4^{3-}, NO_3^-) is a critical determinant of soil structure, nutrient exchange dynamics, and plant nutrient uptake. Elevated calcium and magnesium levels observed in the organic formulations contribute to improved soil aggregation, buffering capacity, and structural stability (Zhu *et al*., 2019; Li *et al*., 2021). Conversely, the relatively high sodium concentrations in vermicompost + vermitea (195.19 mg/L) and NPK fertilizer (167.04 mg/L) may pose potential risks of salinity and sodicity. Excessive sodium can displace essential cations from soil exchange sites, thereby reducing permeability and impairing soil structure (Xu et al., 2020). Nonetheless, the presence of humic substances and organic matter in vermicompost-based treatments can mitigate these effects by enhancing cation exchange capacity and water retention. This buffering mechanism underscores the ecological advantage of organic amendments even under conditions of elevated sodium levels.

4.1.3. pH Variation and Soil Reaction among the Samples

Sample A (Vermicompost) and Sample B (Soil) recorded the highest pH values of 7.43 and 7.45, respectively, indicating slightly alkaline conditions. In contrast, Sample C (Vermitea) and Sample D (NPK Fertilizer) showed lower pH values of 6.69 and 6.77, reflecting more acidic tendencies. Sample E (Vermicompost + Vermitea) exhibited a moderate pH value of 7.06, suggesting a balanced condition between acidity and alkalinity. This data therefore reveals that vermicompost application maintains a near-neutral pH, while the use of vermitea or NPK fertilizer tends to slightly reduce soil pH.

4.1.4. Nutrient Efficiency and Environmental Sustainability

The observed nutrient variability among treatments underscores the fundamental trade-offs between the immediate nutrient efficiency of inorganic fertilizers and the long-term sustainability benefits of organic inputs. While inorganic fertilizers rapidly supply plant-available nutrients, they are often associated with nitrate leaching, soil acidification, and the decline of beneficial soil biota (Bai *et al*., 2020; Hina, 2024; Zhang *et al*., 2024). In contrast, biofertilizers enrich the soil with organic carbon and beneficial microorganisms, fostering microbial biomass growth, enzymatic activity, and nutrient retention (Li *et al*., 2023; Ali *et al*., 2024). The moderate nitrogen content recorded in the vermicompost + vermitea treatment (1.68%) reflects a balanced nutrient profile that sustains soil fertility while minimizing the ecological risks linked to synthetic fertilizers. This balance highlights the potential of integrated organic formulations as viable alternatives for promoting soil health, nutrient efficiency, and environmental sustainability.

Furthermore, the integrated nutrient management (INM) perspective emerging from this study suggests that combining organic and inorganic amendments can achieve the dual goal of high crop productivity and soil health preservation. Such integration enhances nutrient-use efficiency, promotes microbial balance, and reduces the dependency on costly synthetic inputs, thereby aligning with circular economy principles and climate-smart agriculture strategies.

4.0 Conclusion and Recommendations

4.1 Conclusion

The findings demonstrate that nutrient concentrations among the analyzed treatments varied significantly across all six macronutrients. Organic biofertilizers, particularly the combination of vermicompost and vermitea exhibited enhanced enrichment of calcium and magnesium, moderate potassium and nitrogen levels, and a balanced nutrient-release profile that supports long-term soil health. In contrast, NPK fertilizer provided substantially higher concentrations of potassium, phosphorus, and nitrogen but limited secondary nutrients and posed higher risks of salinity and nutrient leaching.

The study confirms that biofertilizers could outperform inorganic fertilizers in promoting balanced nutrient cycling, microbial activity, and sustainable soil fertility, while integrated organic–inorganic fertilization offers the most agronomically and ecologically effective approach to nutrient management.

4.2 Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance soil fertility, nutrient efficiency, and environmental sustainability under both organic and inorganic nutrient management systems:

The combined application of organic (vermicompost + vermitea) and inorganic (NPK) fertilizers is recommended to achieve balanced nutrient availability, enhance soil enzymatic activity, and promote microbial proliferation within the rhizosphere. This integrated approach ensures immediate nutrient supply while maintaining long-term soil health and fertility.

To mitigate the risk of sodium accumulation observed in vermicompost-based formulations, it is advisable to dilute vermitea and other organic extracts at ratios ranging from 1:5 to 1:10 before field application. Regular monitoring of soil electrical conductivity (EC) and sodium adsorption ratio (SAR) is also recommended to maintain optimal salinity thresholds and prevent sodicity-related degradation.

Continuous incorporation of vermicompost and other organic residues should be encouraged to improve cation exchange capacity, enhance soil aggregation, and strengthen microbial resilience against chemical stressors. This practice supports the development of stable soil organic matter and contributes to the overall restoration of degraded soils.

Future research should focus on standardizing feedstock composition, moisture regulation, and composting duration to optimize nutrient mineralization—particularly for potassium and magnesium enrichment. Such optimization will improve the consistency and agronomic quality of vermicompost and its derivatives.

Long-term field experiments are necessary to evaluate crop yield responses, nutrient-use efficiency, and shifts in soil microbial community structure under combined organic–inorganic fertilizer regimes. These studies will provide empirical data to refine application rates and nutrient management strategies across different agroecological zones.

There is a need for the development and implementation of agricultural extension programmes aimed at promoting farmer awareness of biofertilizer production, handling, and utilization. Policy frameworks should support integrated soil fertility management (ISFM) as a key component of sustainable agricultural development.

Excessive reliance on synthetic fertilizers should be minimized to reduce nitrate leaching, eutrophication, and soil acidification. Emphasizing organic inputs and circular nutrient management will contribute to a more regenerative, climate-resilient, and environmentally responsible agricultural system.

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