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Vermicomposting of Camel (*Camelus dromedarius*) Manure with Fly Ash and Microbial Inoculants: Effects on Nutrients and Heavy Metals

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Abstract

This study evaluated the effects of fly ash (F) and effective microorganisms (EM) on nutrient dynamics and heavy metal transformations during vermicomposting of camel manure (CM). Four treatments (CM, CM + F, CM + EM, and CM + F + EM) were arranged in a completely randomized design and monitored over 12 weeks. Significant ($p < 0.05$) treatment and time interactions were observed for pH, NH_4-N, Mn, Pb, and Mo. The addition of EM resulted in a greater decline in pH compared to other treatments. After 12 weeks, Olsen P increased from 300.62 to 398.71 mg/kg in CM + EM, while NH_4-N increased markedly from 22.74 to 86.62 mg/kg. In contrast, NO_3/NO_2-N declined in EM-amended treatments but increased in the control and CM + F. Trace metal concentrations generally increased due to mass reduction during vermicomposting yet remained within internationally acceptable limits. Germination index (GI) values varied significantly among crops and treatments, ranging from phytotoxic to non-phytotoxic responses. Although CM + EM produced superior nutrient enrichment, several vegetables exhibited GI values below 50%, indicating potential phytotoxicity for sensitive crops. In case of established crops for which nutrient supply outweighs early phytotoxic concerns, CM + EM represents the most agronomically beneficial option. Future studies should explore blending CM + EM and CM + F with stabilizing amendments such as biochar to optimize nutrient availability while minimizing salinity and phytotoxic risks.

Keywords: effective micro-organisms; heavy metals; extractable phosphorus; *Eisenia fetida*; vermi-degradation; phytotoxicity

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1. Introduction

The advent of climate change-induced land degradation as well as concerns over soil health degradation associated with the overuse of synthetic fertilizer, evolving policy framework promoting sustainable agriculture like the EU Farm to Fork Strategy and increased consumer demand for environmentally friendly food production, has of late resulted in a renewed interest in organic farming systems in agriculture [1,2]. The increase in world population has also resulted in increased industrial food production in agriculture, and this has resulted in organic waste management becoming a critical global challenge, particularly in developing countries [3]. The high production of animals to meet increased meat demand generates huge quantities of animal manure that are sometimes indiscriminately applied to agricultural land, thus further posing environmental challenges [3,4]. This underscores the urgent need for the preservation of the environment through optimized usage of these organic waste resources as part of organic soil fertility management [3].

Apart from the usual cow, pig, and goat manure, camel (*Camelus dromedarius*) manure represents a resource that can be abundantly available in desert and semi-desert areas, especially across North Africa, the Middle East, and parts of Southern Africa [5]. The importance of camels with the advent of climate change is becoming recognized due to their ability to utilize fibrous materials of poor nutritional value, especially in desert areas like Namibia [5]. Over 80% of the world's camels are in Africa and the global population in 2024–25 was over 40 million, with populations expected to reach 60 million by 2040. Owing to the increasing reliance on camels for meat, milk, transport, and cultural value, the volume of camel manure produced continues to rise [6]. Despite its availability in arid countries, camel manure remains widely underutilized and under-researched due to its slower mineralization kinetics and lower short-term nutrient release efficiency compared to other livestock manures. Its high fiber and lignin fractions reduce decomposition rates and nitrogen mineralization efficiency, often extending compost maturity periods beyond 12–16 weeks under standard conditions, relative to faster-decomposing poultry and cattle manures [7]. Traditional thermophilic composting methods are slow and inefficient for such lignin-rich manures; thus, there is a need for innovative approaches that improve camel manure biodegradation, stabilization, and nutrient mineralization [6,7].

One technology that has gained momentum in improving the fertilizer value of organic materials is vermicomposting, where earthworms work together with microorganisms to accelerate decomposition and nutrient mineralization [8,9].

The synergistic activity of earthworms through ingestion, gut-associated transformation, fragmentation of organic residues, and casting, together with microbial enzymatic processes enhances mineralization and humification, resulting in a nutrient-rich, stable, and microbially active product known as vermicompost, with improved aeration occurring indirectly through burrowing activity [10]. Beyond enhancing nutrient release, vermicomposting has been shown to reduce phytotoxicity, suppress pathogens, and transform complex organic molecules into bioavailable forms, making it an effective strategy for managing a wide range of organic wastes [11,12]. In the context of camel manure, vermicomposting offers an opportunity to convert a bulky, lignocellulose material into a value-added soil amendment capable of improving soil structure, moisture retention, and nutrient supply [7].

In recent years, the incorporation of additional materials and microbial additives into vermicomposting systems has gained attention to further enhance process efficiency and product quality [13]. Fly ash, an inorganic industrial by-product generated from coal combustion, has attracted interest as a compost amendment due to its physicochemical characteristics and wide availability [14]. Rich in micro- and macronutrients such as calcium, potassium, magnesium, and trace elements, fly ash can act as a nutrient amendment,

balancing compost pH, and altering the mineral composition of compost substrates [9]. When applied in moderate proportions, fly ash has been shown to stimulate microbial activity, promote humification, and enhance plant nutrient availability [15]. However, concerns persist regarding the presence and mobility of potentially toxic heavy metals such as cadmium, chromium, nickel, and lead within fly ash with concentrations ranging from Cd 39–85 mg kg^{-1}, Ni around 420 mg kg^{-1}, Pb 300–840 mg kg^{-1}, which may pose environmental risks if not adequately stabilized during composting or vermicomposting processes [16]. These concentrations underscore the need to assess both total concentration and bioavailability relative to international standards before land application.

Microbial inoculants like effective micro-organisms (EM)and phosphate-solubilizing bacteria represent another promising enhancement to vermicomposting systems [17]. These EM are a consortium of beneficial microbes which typically include *Lactobacillus*, *Saccharomyces* and *Streptomyces* spp., whose synergistic activities can be used to enhance compost biodegradation, nutrient cycling and pathogen suppression making them effective in improving compost quality [17]. The deliberate introduction of beneficial microorganisms such as cellulolytic bacteria, lignin-degrading fungi, phosphate-solubilizing microbes, and nitrogen fixers can accelerate the breakdown of complex organic polymers, therefore promoting the release and availability of key nutrients through enhanced mineralization, and improvement of earthworm growth and activity by increasing palatability [18,19]. These inoculants contribute to higher enzymatic activity, faster decomposition, and improved humus formation. Moreover, certain microbial strains stabilize heavy metals not only through biosorption, bioaccumulation, and transformation but also by altering metal speciation and binding to specific functional groups (e.g., carboxyl, hydroxyl, and phosphate sites) in organic matter and microbial biomass, thereby reducing bioavailability and improving the environmental safety of compost products. The combined use of microbial inoculants with fly ash in a vermicomposting system has the potential to create synergistic effects that enhance both nutrient dynamics and heavy metal immobilization [15].

Despite the growing interest in vermicomposting enhancement strategies, limited studies have examined the co-application of fly ash and microbial inoculants in the vermicomposting of camel manure, which has been done with other animal manures. This gap is particularly significant given the unique chemical composition and physical structure of camel manure, which differs from other livestock manures such as cattle or goat manure [20,21]. Furthermore, the dual challenge of nutrient enrichment and heavy metal stabilization when incorporating fly ash requires careful scientific assessment. Understanding how earthworms respond to such substrates, how microbial inoculants affect decomposition, and how heavy metals behave throughout the vermicomposting process is essential for ensuring the safety and agronomic value of the final vermicompost. In light of these considerations, this study evaluated the effects of fly ash and selected microbial inoculants on nutrient transformation and heavy metal changes in camel manure–based vermicompost. Specifically, the research investigated changes in physio-chemical properties (pH, electrical conductivity, P, N, and selected heavy metals) of fly ash and effective micro-organism-amended camel manure vermicompost.

2. Materials and Methods

2.1. Source of Materials Used in the Study

The study was undertaken at the University of Namibia's Sam Nujoma Campus (−22.096472° S, 14.260281° E) in Henties Bay, Erongo Region of Namibia. The vermicomposting was undertaken in rectangular vermi-bins (L 65 cm × W 45 cm × 20 cm) with perforations at the bottom and a collecting pan to allow for drainage of excess moisture. The camel dung came from a farm in the Swakopmund, Erongo region of Namibia. The

camels, kept mainly in captivity for tourism in Swakopmund, were fed a diet of dry grass supplemented with fresh common reeds, and manure was collected following a standardized protocol to ensure representative quality. The manure was collected dry already from the camel kraal, and any grass and other sticks were removed before storing the manure under shade for further use. The fly ash used in this study was sourced from Matla power station (26.28250° S 29.14083° E) located in the Mpumalanga province of South Africa. The microbial inoculant used was Effective Microorganisms, a synergistic, mixed culture of beneficial, naturally occurring, food-grade microorganisms. The EM used in this study was the Solutions 4 EM sourced from a local South African supplier (Lindoros Whole Earth Consultants, Rivonia, South Africa). The formulation was based on the effective microorganism technology which involves the use of a blend of microbes such as *Lactobacillus acidophilus*; *Lactobacillus delbrueckii* subsp. *Bulgaricus*; *Lactobacillus brevis*; *Lactococcus lactis*; *Streptococcus thermophilus*; *Bifidobacterium animalis* ssp. *Lactis*; *Bifidobacterium bifidum*; *Bifidobacterium longum*; among other microorganisms used to improve soil health, plant growth, and overall ecosystem balance, though the full composition of the EM is withheld from the public.

Table 1 indicates the initial characteristics of the camel manure and fly ash used in this study.

Table 1. Selected properties of original materials (camel manure and fly ash) used in this study.

Parameter *	Camel Manure	Fly Ash
pH	7.57 ± 0.04	11.65 ± 0.10
Electrical conductivity (mS/cm)	10.60 ± 0.50	2.44 ± 0.39
Olsen P (mg/kg)	184.56 ± 42.60	365.44 ± 26.70
Nitrate/Nitrite (mg/kg)	164.44 ± 13.66	34.16 ± 1.78
Ammonium (mg/kg)	215.17 ± 13.43	13.87 ± 3.32
As (mg/kg)	6.26 ± 1.63	7.93 ± 0.46
Cu (mg/kg)	50.93 ± 2.02	64.87 ± 9.80
Co (mg/kg)	11.10 ± 1.74	14.13 ± 1.74
Ni (mg/kg)	24.40 ± 1.54	28.63 ± 0.50
Mn (mg/kg)	137.33 ± 10.41	167.00 ± 22.52
Pb (mg/kg)	21.87 ± 4.78	31.63 ± 11.63
Mo (mg/kg)	6.28 ± 0.49	11.50 ± 0.79

Values are mean ± Standard deviation (n = 3); * Samples analyzed using methods described under Sample analysis.

2.2. Treatments, Experimental Design and Establishment

2.2.1. Experimental Design

The study was conducted using a completely randomized design (CRD) comprising four treatments with three replicates each (n = 12 experimental units). The treatments were: (i) camel manure (CM); (ii) CM amended with fly ash (CM + F); (iii) CM inoculated with effective microorganisms (CM + EM); and (iv) CM amended with both fly ash and effective microorganisms (CM + F + EM). Each replicate consisted of 3 kg substrate (dry weight basis) placed in separate vermicomposting containers.

2.2.2. Substrate Preparation and Treatment Formulation

Camel manure was homogenized and mixed with shredded wastepaper to adjust the initial carbon-to-nitrogen (C/N) ratio to approximately 30:1, based on previously determined optimum C and N concentrations of the raw materials [15]. All components were weighed on a dry weight basis. Fly ash was incorporated into the designated treatments at a CM:F ratio of 2:1 (w/w) based on the recommendations of [15]. The materials were thoroughly mixed to ensure uniform distribution. Effective microorganisms (EM) were

applied to the relevant treatments at a rate of 500 mL kg^{-1} substrate, without any dilution prior to application. The EM solution was evenly sprayed onto the substrate during mixing to ensure homogeneous inoculation.

2.2.3. Moisture Adjustment and Pre-Composting

Moisture content of all substrates was adjusted to approximately 60–70% (wet basis) using deionized water and maintained throughout the experiment by periodic rewetting. The prepared substrates were pre-composted aerobically for 7 days to allow dissipation of excessive heat and volatile compounds. During this period, the mixtures were manually turned to enhance aeration.

2.2.4. Vermicomposting Procedure

After pre-composting, mature clitellated earthworm species: *Eisenia fetida* were introduced at a stocking density of 25 g fresh worm biomass kg^{-1} substrate, following previously published recommendations [22]. Vermicomposting was conducted for 12 weeks under ambient laboratory conditions with temperature ranging from 20–30 °C. Moisture content was maintained at 60–70% throughout the experimental period.

2.2.5. Sampling and Laboratory Analysis

Composite samples were collected from each experimental unit at week 0 (prior to worm introduction) and week 12 (end of vermicomposting). Samples were sealed in plastic bags and stored frozen until analysis. Prior to laboratory determinations, samples were thawed, oven-dried at 70 °C for 48 h, and ground to pass through a 2 mm sieve using an electric grinder. The processed samples were analyzed for selected physicochemical properties following standard analytical procedures described below.

2.3. Sample Analysis

2.3.1. pH and Electrical Conductivity

For pH and electrical conductivity (EC), 10 g sample was weighed into an extraction bottle, and 100 mL of deionized water was added. This method has already been successfully applied and is described in more detail by [23]. Briefly, a 10 g of ground compost sample was weighed into a sampling bottle and 100 mL of deionized water was added. The mixture was then shaken on a reciprocating shaker at 120 rpm for 1 h, after which the pH and EC were measured in the supernatant using a multi-parameter meter equipped with a glass electrode (HQ11d portable meter, HACH).

2.3.2. Olsen Extractable Phosphorus

A solution of 0.5 M sodium hydrogen carbonate, adjusted to a pH of 8.5 using 1 M sodium hydroxide, was used for extraction [24]. Briefly, 2.5 g of compost was shaken in 50 mL of the extracting solution for 30 min at 120 rpm and then filtered with Whatman No. 2 filter paper. The extracts were then analyzed for P using the ascorbic acid method [25].

2.3.3. Extractable Nitrate, Nitrite and Ammonium

Extractable inorganic nitrogen fractions (NH_4^+ and NO_2/NO_3-) were extracted using 0.5 M potassium sulfate [26]. Briefly, 5 g of the compost sample was shaken for an hour on a mechanical reciprocal shaker at 180 rpm and filtered through Whatman No. 2 filter paper for colorimetric analysis using a UV spectrophotometer (Genesys 105 UV-Vis, Thermo Fisher Scientific, Waltham, MA, USA). Nitrate, nitrite, and ammonium levels were determined colorimetrically [26]. Briefly, for NH_4^+-N, the filtered extract was reacted sequentially with N1 and N2 reagents, and the resulting blue color intensity was measured at 655 nm using a UV-Vis spectrometer (Genesys 10S, Thermo Fisher Scientific, Waltham, MA, USA),

calibrated with standards ranging from 0 to 25 µg NH_4^+-N mL^{-1}. For NO_2/NO_3-N determination, the extract was reacted with salicylic acid and NaOH solutions [26], and absorbance was read at 419 nm using spectrometer calibrated with standards ranging from 0 to 10 µg NO_3-N mL^{-1}.

2.3.4. Total Heavy Metal Content

Dried and ground samples analyzed for heavy metal determination were initially digested using analytical reagent-grade perchloric acid and nitric acid. A 0.5 g sample of compost was digested with 10 mL of nitric acid (60%), heated at 150 °C for 30 min, before adding 4 mL of perchloric acid (65%), and heated again for 30 min at the same temperature. The digested samples were then made up to a volume of 500 mL and filtered using Whatman number 2 filter paper. The digested samples were subsequently analyzed for various heavy metals using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Shimadzu Corporation, Kyoto, Japan).

2.4. Data Analysis

All data collected were analyzed using JMP version 18 Student Version statistical software (SAS Institute, Inc., Cary, NC, USA, 1989–2023). Since the same experimental units were sampled at week 0 and week 12, the observations were not independent over time; therefore, repeated measures analysis of variance (ANOVA) was used to account for within-unit temporal correlation. Where sphericity assumptions could not be met, the Greenhouse–Geisser correction of P was used. For the phytotoxicity study, where statistical significance was observed, Fisher's Protected Least Significant Difference (LSD) was used for mean separation at $p < 0.05$. Graphs were plotted using GraphPad Prism version 8 for Windows (GraphPad Software, https://www.graphpad.com/, accessed on 25 December 2025).

3. Results

3.1. Changes in pH and Electrical Conductivity in Fly Ash and Effective Micro-Organism-Amended Camel Manure Vermicompost

There was a significant difference ($p < 0.05$) between the treatments on changes in pH. Over the course of 12 weeks of vermicomposting, a significant treatment × time interaction was observed, indicating that changes over time differed among treatments (Table 2). Generally, the addition of fly ash, effective microorganisms, or both, in the vermicompost reduced the pH over time, whereas in unamended vermicompost, the pH remained almost unchanged (Figure 1A). The pH in unamended vermicompost (control) remained at a pH value of 8.08 at both week 0 and after 12 weeks of vermicomposting (Figure 1A). The addition of fly ash alone (CM + F) decreased the pH from 8.75 to 8.38 after 12 weeks, while the addition of effective microorganisms (CM + EM) alone decreased the pH from 8.50 at week 0 to 7.74 after 12 weeks (Figure 1A). Meanwhile, the addition of both fly ash and effective microorganisms (CM + F + EM) decreased the pH from 8.75 at week 0 to 8.37 after 12 weeks of vermicomposting (Figure 1A). After 12 weeks of vermicomposting, the highest pH was observed in CM + F with a value of 8.38, followed by CM + F + EM > control > CM + EM with the lowest pH value of 7.74 (Figure 1A).

Though there were no significant differences between treatments, there was a significant change with time in electrical conductivity (EC) ($p < 0.05$) across the 12 weeks of vermicomposting (Table 2). The electrical conductivity of the vermicompost increased throughout the 12 weeks of vermicomposting, except in the CM + F + EM treatment, where the EC was lower after 12 weeks (Figure 1B). In the control treatment, the EC increased from 3.94 mS/cm at week 0 to a value of 6.16 mS/cm after 12 weeks of vermicomposting

(Figure 1B). The inclusion of fly ash increased the EC from a value of 3.78 mS/cm at week 0 to 5.52 mS/cm after 12 weeks, whilst the addition of effective microorganisms increased the EC from 3.81 mS/cm to 7.41 mS/cm (Figure 1B). In contrast, the EC in the CM + F + EM treatment decreased from 4.48 mS/cm to an EC value of 4.28 mS/cm at week 12 (Figure 1B). After 12 weeks of vermicomposting, the highest EC was observed in CM + EM with an EC value of 7.41 mS/cm, followed by the control with 6.16 mS/cm, CM + F with a value of 5.52 mS/cm, and CM + F + EM with the lowest EC values of 4.28 mS/cm (Figure 1B).

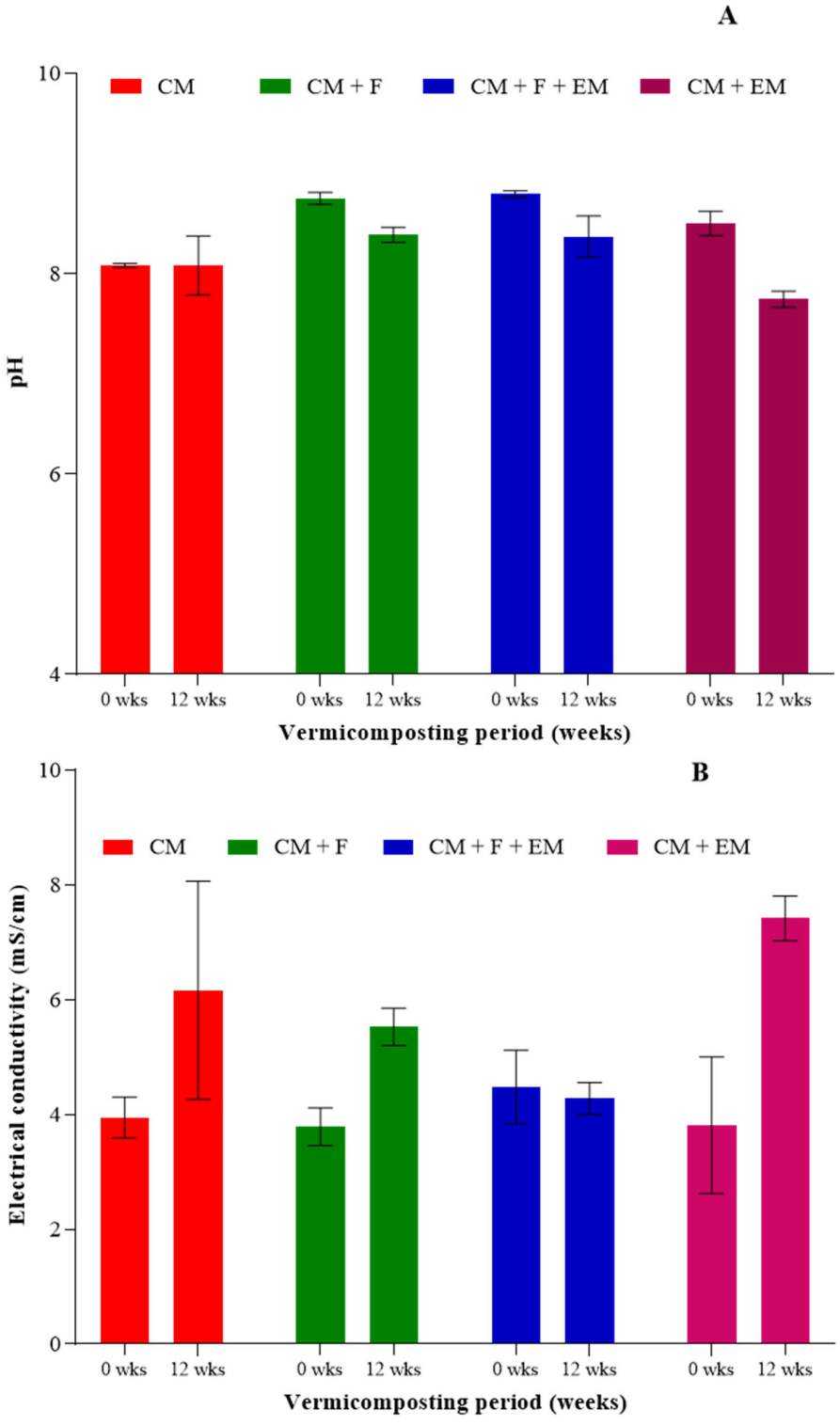

Figure 1. Changes in pH (**A**) and electrical conductivity (**B**) following 12 weeks of vermicomposting of camel manure (CM) amended with fly ash (F) and effective micro-organisms (EM), $n = 3$.

Table 2. Repeated measures analysis of variance (ANOVA) for changes in selected chemical properties during vermicomposting of camel manure over a 12-week period.

Parameters	Between Subjects		Within Subjects			
	Treatments (Trt)		Time		Trt × Time	
	F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value
pH	27.32	0.0007	47.58	0.0005	7.68	0.0177
EC (mS/cm)	2.54	ns	22.76	0.0031	4.16	ns
Olsen P (mg/kg)	1.04	ns	5.14	ns	0.99	ns
Nitrate/Nitrite (mg/kg)	3.35	ns	4.48	ns	3.48	ns
Ammonium (mg/kg)	23.24	0.001	69.86	<0.0001	39.57	<0.0001
As (mg/kg)	0.71	ns	17.58	0.0057	3.50	ns
Cu (mg/kg)	4.58	ns	4.51	ns	0.63	ns
Co (mg/kg)	3.65	ns	1.79	ns	0.34	ns
Ni (mg/kg)	0.36	ns	0.04	ns	2.89	ns
Mn (mg/kg)	6.70	0.0242	159.73	<0.0001	0.45	ns
Pb (mg/kg)	26.34	0.0007	0.93	ns	12.29	0.0057
Mo (mg/kg)	18.56	0.0019	1.65	ns	9.07	0.012

"ns" stands for "not significant".

3.2. Changes in Macronutrients (N, P) in Fly Ash and Effective Micro-Organism-Amended Camel Manure Vermicompost

There was no significant difference ($p > 0.05$) between the treatments in the changes in Olsen P (mg/kg), and there was no significant influence of time on the changes in Olsen P (Table 2). In the control, the Olsen P values increased from 290.11 mg/kg to 385.90 mg/kg from week 0 to week 12, respectively (Figure 2). In the CM + F treatment, the Olsen P values increased from 353.39 mg/kg to 372.33 mg/kg, while in the CM + EM, the Olsen P concentration values increased from 300.62 mg/kg to 398.71 mg/kg, from week 0 to week 12, respectively (Figure 2). Unlike in other treatments where the Olsen P increased over time, in the CM + F + EM treatment, the P concentration values reduced from 374.05 mg/kg at week 0 to a value of 372.33 after 12 weeks (Figure 2). After 12 weeks of vermicomposting, the Olsen P concentration values followed the order: CM + EM > CM + F > CM + F + EM, with values ranging from 372.33 mg/kg to 398.71 mg/kg (Figure 2).

There was no significant difference ($p > 0.05$) between the treatments in the changes in nitrites/nitrites (NO_3/NO_2-N) concentrations (Table 2). In the unamended vermicompost, the NO_3/NO_2-N concentration values increased from 74.84 mg/kg to 111.93 mg/kg, while in the CM + F treatment the values increased from 68.23 mg/kg to 104.22 mg/kg from week 0 to week 12, respectively (Figure 3A). In the CM + EM treatment, the NO_3/NO_2-N values decreased from 116.52 mg/kg to 110.30 mg/kg, whilst in the CM + F + EM the concentration decreased from 76.08 mg/kg to 68.08 mg/kg from week 0 to week 12, correspondingly (Figure 3A). At week 12, treatments followed the order CM + EM > CM > CM + F > CM + F + EM, with NO_3/NO_2-N values ranging from 68.08 mg/kg to 111.93 mg/kg (Figure 3A).

There was a significant difference ($p < 0.05$) between the treatments in the changes in ammonium-N (NH_4-N) (mg/kg) (Table 2). Throughout the vermicomposting period, we observed a significant change in ammonium-N, indicating an interaction between treatments and time (Table 2). In the control (CM), the values decreased from an NH_4-N concentration value of 74.84 mg/kg at week 0 to a value of 55.41 mg/kg after 12 weeks (Figure 3B). In the CM + F, the NH_4-N values increased from 1.41 mg/kg at week 0 to 41.49 mg/kg after 12 weeks, while in the CM + EM treatment, the NH_4-N values increased from 22.74 mg/kg at week 0 to 86.62 mg/kg at week 12 (Figure 3B). The inclusion of both fly ash and effective microorganisms in the vermicompost increased the NH_4-N

concentration from 15.10 mg/kg at week 0 to 45.53 mg/kg after 12 weeks (Figure 3B). After 12 weeks of vermicomposting, the highest NH_4-N concentration was recorded in the CM + EM treatment with a value of 86.62 mg/kg, and the lowest was recorded in the CM + F treatment with a value of 45.53 mg/kg (Figure 3B).

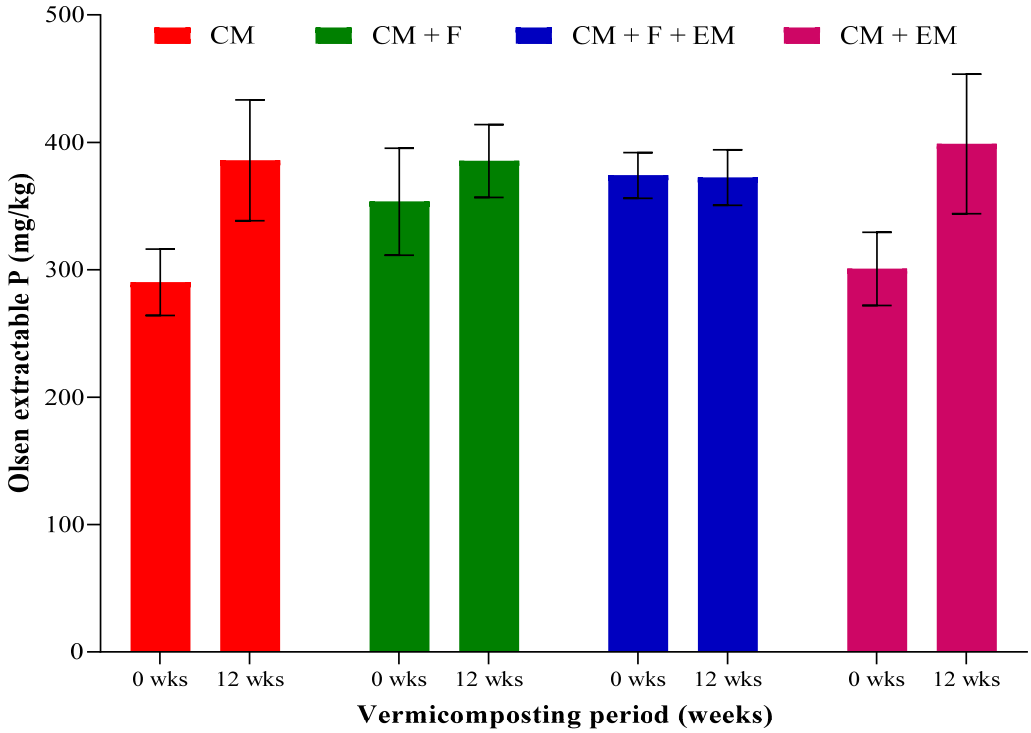

Figure 2. Changes in Olsen extractable phosphorus following 12 weeks of vermicomposting of camel manure (CM) amended with fly ash (F) and effective micro-organisms (EM), $n = 3$.

3.3. Changes in Trace Metals in Fly Ash and Effective Micro-Organism-Amended Camel Manure Vermicompost

There was a significant change ($p < 0.05$) in arsenic (As) (mg/kg) across the 12 weeks of vermicomposting (Table 2). The As concentration significantly increased over time in all treatments, except in the CM + F + EM treatment, where it decreased after 12 weeks (Figure 4A). In the control, As concentration values ranged from 2.75 mg/kg at week 0 to 5.96 mg/kg observed at week 12 (Figure 4A). In the CM + F treatment, the lowest recorded As concentration was 2.73 mg/kg at week 0, while the highest recorded value was 6.55 mg/kg after 12 weeks (Figure 4A). In the CM + EM treatment, the concentration values ranged from 3.90 mg/kg to 7.62 v mg/kg at week 0 and week 12, respectively (Figure 4A). Unlike in other treatments where arsenic concentration increased over time, in the CM + F + EM treatment, the concentration decreased from a value of 5.98 mg/kg at week 0 to 5.16 mg/kg after 12 weeks (Figure 4A). At week 12, the highest As concentration was recorded in the CM + EM treatment with 7.62 mg/kg, while the lowest was recorded in the CM + F + EM treatment with a value of 5.16 mg/kg (Figure 4A). After 12 weeks of vermicomposting, in terms of As concentration, the treatments followed the order CM + EM > CM + F > CM > CM + F + EM (Figure 4A).

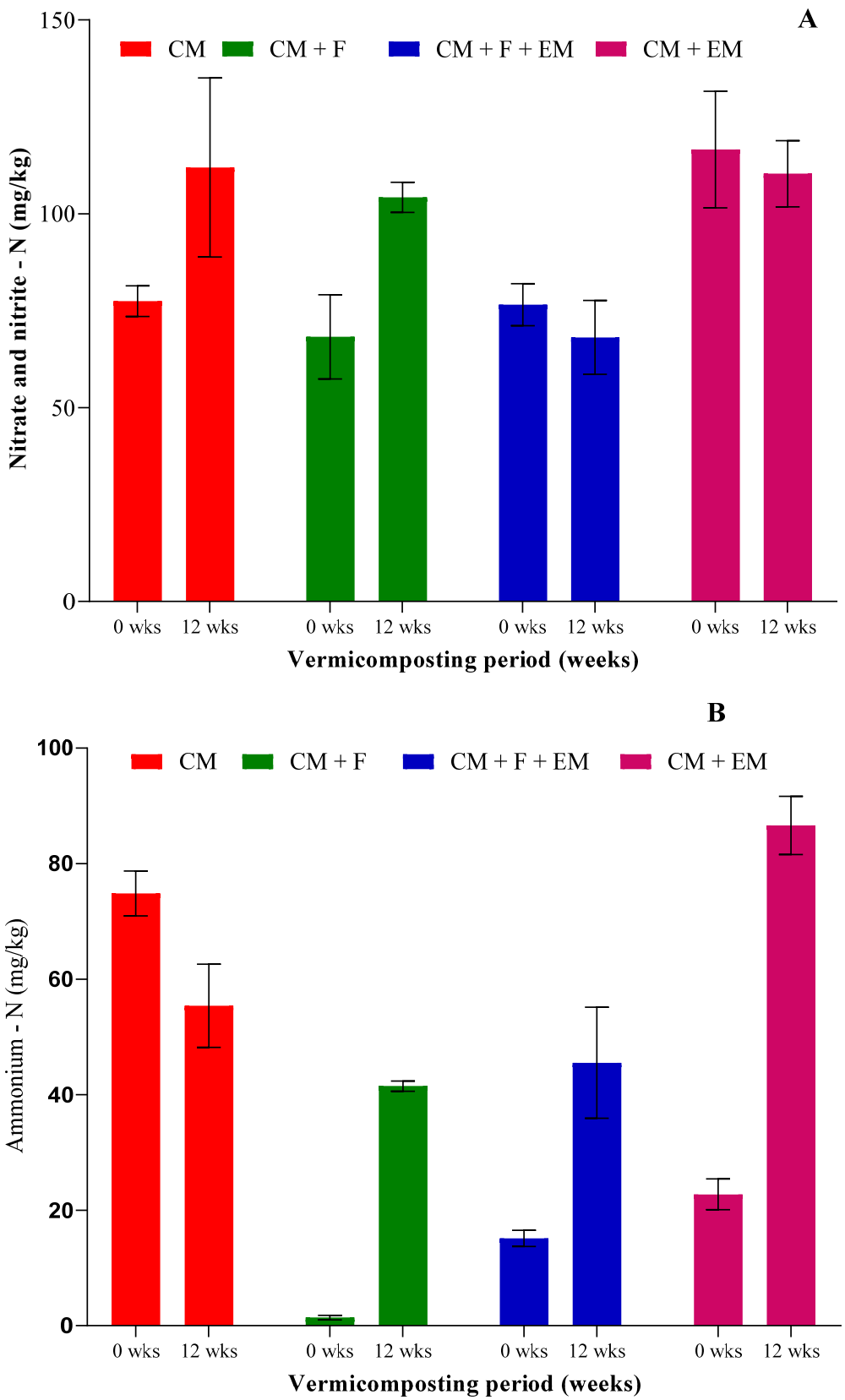

Figure 3. Changes in nitrate nitrite (**A**) and ammonium (**B**) following 12 weeks of vermicomposting of camel manure (CM) amended with fly ash (F) and effective micro-organisms (EM), $n = 3$.

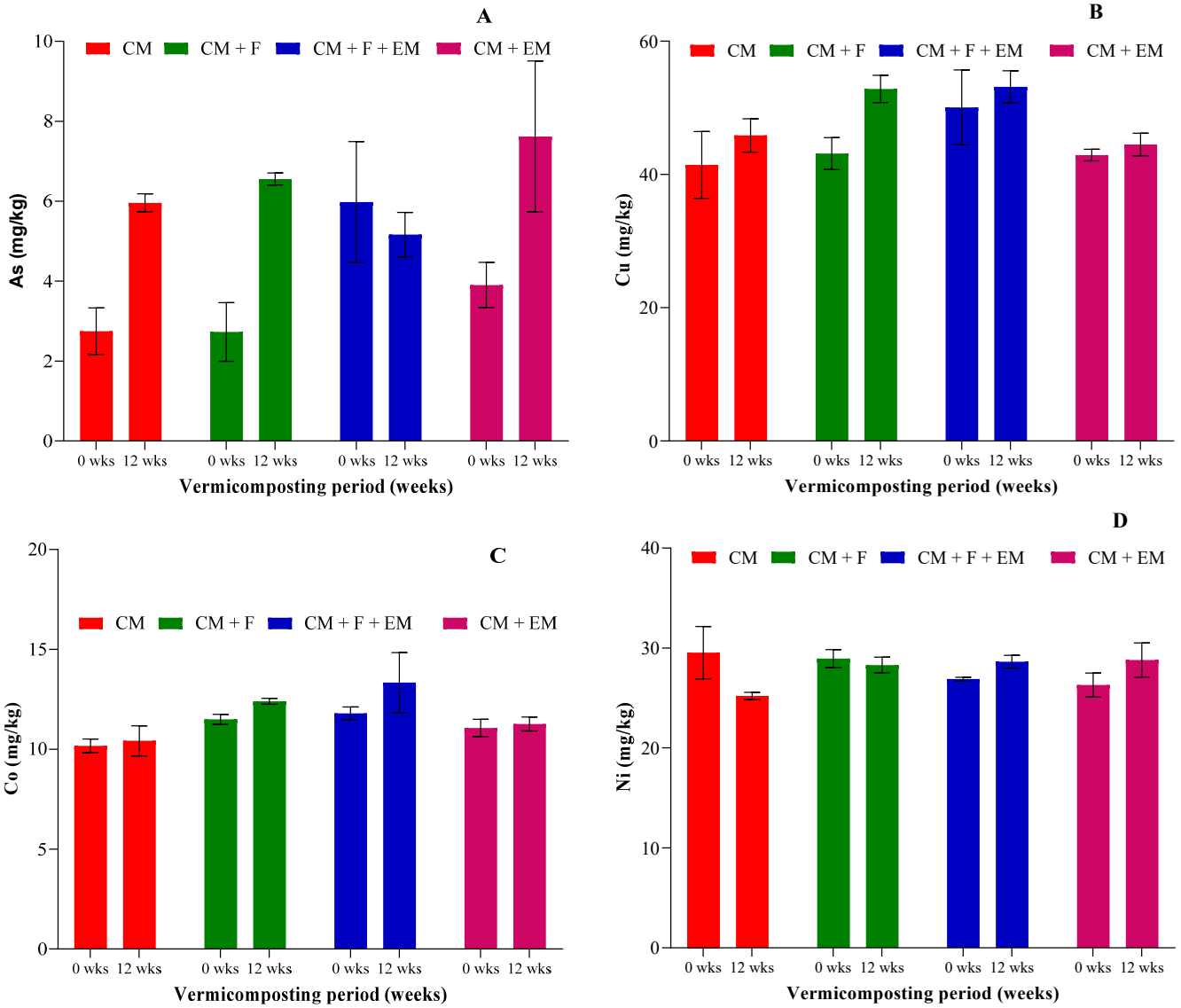

Figure 4. Changes in heavy metals As (**A**); Cu (**B**); Co (**C**) and Ni (**D**) after 12 weeks of vermicomposting of camel manure (CM) amended with fly ash (F) and effective micro-organisms (EM), $n = 3$.

There was no significant difference ($p > 0.05$) between the treatments in the changes in copper (Cu) concentrations (mg/kg), and there was no significant influence ($p > 0.05$) of time on the changes in Cu (mg/kg) (Table 1). Across all treatments, the Cu concentrations were insignificantly higher at week 12 than at week 0 (Figure 4B). In the CM treatment, the Cu concentrations ranged from a value of 41.43 mg/kg at week 0 to 45.87 mg/kg after 12 weeks (Figure 4B). In the CM + F treatment, the Cu concentration ranged from 43.13 mg/kg to 52.83 mg/kg, while in the CM + EM treatment, the values ranged from 42.9 mg/kg to 44.50 mg/kg from week 0 to week 12, respectively (Figure 4B). In the CM + F + EM treatment, Cu concentration increased from 50.07 mg/kg at week 0 to 53.17 mg/kg at week 12 (Figure 4B). After the 12-week period, Cu concentration in treatments followed the order CM + F + EM > CM + F > CM > CM + EM, with values ranging from 44.50 mg/kg to 53.17 mg/kg (Figure 4B).

There was no significant difference ($p > 0.05$) between the treatments in terms of changes in cobalt (Co) concentrations (mg/kg) (Table 1). Furthermore, there was no significant influence ($p > 0.05$) of time on the changes in Co (mg/kg) (Table 1). The Co concentra-

tions insignificantly increased over time in all the treatments (Figure 4C). In the control, the Co concentration increased from 10.17 mg/kg at week 0 to 10.42 mg/kg at week 12 (Figure 4C). In the CM + F, the Co concentration increased from a value of 11.5 mg/kg to 12.4 mg/kg, while in the CM + EM treatment, values increased from 11.07 mg/kg to 11.27 mg/kg, from week 0 to week 12, respectively (Figure 4C). In CM + F + EM, the Co concentrations ranged from a value of 11.07 mg/kg recorded at week 0 to 11.27 mg/kg at week 12 (Figure 4C). After 12 weeks the highest Co concentration of 13.33 mg/kg was recorded in the CM + F + EM treatment, while the lowest concentration of 10.42 mg/kg was observed in the control (Figure 4C).

There was no significant difference ($p > 0.05$) between the treatments in terms of changes in Ni concentrations (mg/kg) (Table 1). Furthermore, there was no significant influence ($p > 0.05$) of time on the changes in Ni concentrations (Table 1). The Ni concentration increased insignificantly over time in the CM + EM and CM + F + EM treatments, while in the control and CM + F treatments, it exhibited an insignificant reduction over time (Figure 4D). In the control, the Ni values ranged from 25.20 mg/kg at week 12 to 29.53 mg/kg at week 0, while in the CM + F treatment, the Ni concentration values ranged from 28.93 mg/kg at week 0 to 28.30 mg/kg at week 12 (Figure 4D). In the CM + EM treatment, the Ni concentration values increased from 26.30 mg/kg to a value of 28.80 mg/kg, whilst in the CM + F + EM treatment, the values increased from 26.90 mg/kg to 28.63 mg/kg, from week 0 to week 12, respectively (Figure 4D). After 12 weeks, the highest Ni concentration value was recorded in the CM + EM treatment, followed by CM + F + EM > CM + F > CM, with concentration values ranging from 25.20 mg/kg to 28.80 mg/kg (Figure 4D).

There was a significant difference ($p < 0.05$) between the treatments on changes in manganese (Mn), and there was a significant influence of time on changes in Mn concentration in the vermicompost (Table 2). However, there were no significant interactions ($p > 0.05$) between time and treatments in the changes in Mn concentrations of the vermicompost (Table 2). Across all treatments, the Mn concentrations significantly increased from week 0 to week 12 (Figure 5A). In the control treatment, the Mn concentration ranged from 77.67 mg/kg at week 0 to 142.67 mg/kg at week 12 (Figure 5A). In the CM + F, the Mn concentration increased from the value of 99.93 mg/kg to a value of 153.00 mg/kg, while in the CM + EM, the concentration values increased from 87.48 mg/kg to 149.67 mg/kg, from week 0 to week 12, respectively (Figure 5A). In the CM + F + EM treatment, the highest Mn concentration was 155.67 mg/kg recorded at week 12, while the lowest value was 103.67 mg/kg recorded at week 0 (Figure 5A). After 12 weeks, the lowest Mn concentration value was 142.67 mg/kg recorded in the control, while the highest was 155.67 mg/kg recorded in the CM + F + EM treatment (Figure 5A).

There was a significant difference ($p < 0.05$) between the treatments in the changes in lead (Pb) concentrations (mg/kg) in the vermicompost. There was also a significant interaction between treatment and time in the changes in Pb concentrations (mg/kg) in the vermicompost (Table 2). Across all the treatments, the Pb concentration was significantly higher at week 12 than at week 0, except in the CM + EM treatment, where the concentration was significantly lower at week 12 than at week 0 (Figure 5B). In CM alone, the Pb concentration values ranged from 18.07 mg/kg at week 0 to 14.33 mg/kg at week 12 (Figure 5B). In the CM + F treatment the Pb concentration values increased from 28.1 mg/kg to 32.00 mg/kg, while in the CM + F + EM treatment the values increased from 16.5 mg/kg to 25.60 mg/kg, from week 0 to week 12, respectively (Figure 5B). After 12 weeks, the Pb concentration values in treatments followed the order CM < CM + EM < CM + F < CM + F + EM, with values ranging from 14.33 mg/kg to 32.00 mg/kg (Figure 5B).

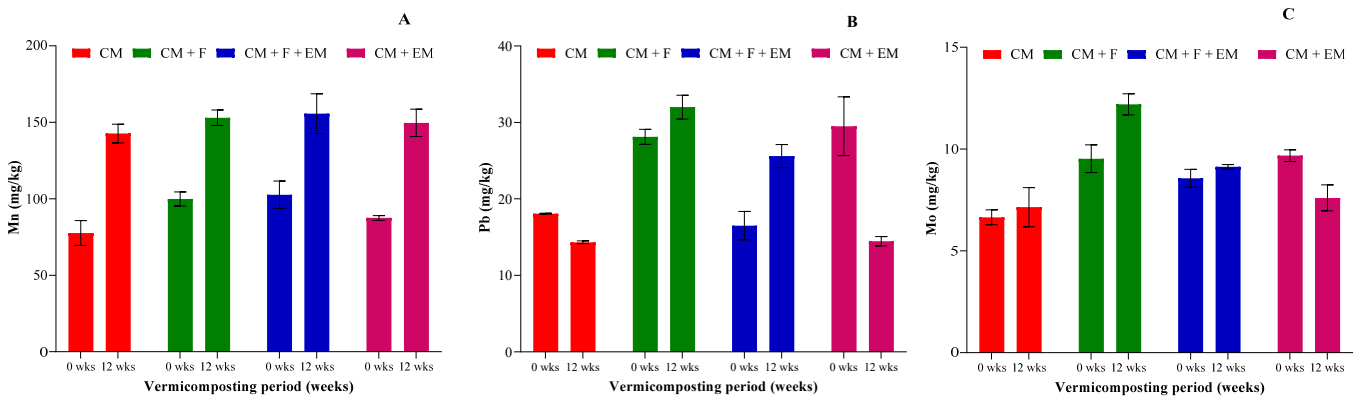

Figure 5. Changes in Mn (**A**); Pb (**B**) and Mo (**C**) following 12 weeks of vermicomposting of camel manure (CM) amended with fly ash (F) and effective micro-organisms (EM), $n = 3$.

There was a significant difference ($p < 0.05$) between the treatments in the changes in molybdenum (Mo) concentrations in the vermicompost (mg/kg). Furthermore, there was a significant interaction ($p < 0.05$) between treatment and time on the changes in Mo concentration (mg/kg) (Table 2). Across all the treatments, the Mo concentration was higher at week 12 than at week 0, except in the CM + EM treatment, where the concentration was lower at week 12 than at week 0 (Figure 5C). In the control treatment, the Mo concentration values ranged from 6.65 mg/kg recorded at week to 7.15 mg/kg at week 12. In the CM + F treatment, the Mo concentration increased from 9.52 mg/kg at week 0 to a value of 12.2 mg/kg at week 12 (Figure 5C). In contrast, in the CM + EM treatment, the Mo concentration values decreased from 9.68 mg/kg at week 0 to 7.60 mg/kg after 12 weeks (Figure 5C). In the CM + F + EM treatment, the Mo concentration increased from 8.57 mg/kg at week 0 to 9.13 mg/kg after 12 weeks (Figure 5C). After 12 weeks of vermicomposting, the Mo concentration ranged from 7.15 mg/kg to 12.2 mg/kg, with the lowest value recorded in the control and the highest value recorded in the CM + F treatment (Figure 5C).

3.4. Effects of Fly Ash and Effective Micro-Organisms—Amended Camel Manure Vermicompost—On Crop Phytotoxicity

There was a significant influence ($p < 0.05$) of treatments on the relative seed germination (RSG) for onion, radish, and tomato, while there were no significant differences in the RSG values between treatments in cabbage and Swiss chard (Table 3). The RSG response trends were not consistent across treatments in the tested vegetables (Table 3). The radish in the C + F treatment had the highest RSG, at 126.98%. The Swiss chard in the CM and CM + F + EM treatments had the lowest RSG, at 40.00% (Table 3). The CM + F + EM and CM + EM treatments had the lowest RSG value in cabbage, which was 70.00%. The CM and CM + F treatments had the highest RSG value, which was 90.00% (Table 3). In onions, the RSG values ranged from 65.50% observed in the control to 99.97% recorded in the CM + F + EM treatment (Table 3). The RSG values in radish ranged from 68.38% in the CM + F + EM treatment to the RSG value of 126.98% in the CM + F treatment (Table 3). In Swiss chard, the RSG values ranged from 40.0% recorded in both the CM and CM + F + EM treatments, to a value of 66.67% recorded in the CM + F treatment (Table 3). In tomato, the RSG values ranged from 83.33% in the CM + F treatment to 105.56% in the control treatment (Table 3).

Table 3. Phytotoxic properties of different treatments based on camel manure amended with fly ash and effective micro-organisms on selected vegetable crops.

Crop	Parameter	Treatments			
		CM	CM + F	CM + F + EM	CM + EM
Cabbage	RSG	90.00 a *	90.00 a	70.00 a	76.67 a
	RRE	25.67 c	67.65 a	64.17 a	49.77 b
	GI	16.90 c	60.46 a	51.81 ab	38.05 b
Onion	RSG	65.50 b	96.52 a	99.97 a	96.52 a
	RRE	45.70 b	63.33 a	76.64 a	44.28 b
	GI	29.38 c	61.42 ab	76.88 a	42.64 bc
Radish	RSG	68.78 b	126.98 a	68.38 b	71.43 b
	RRE	188.86 a	132.54 a	159.49 a	158.06 a
	GI	154.28 a	156.95 a	156.45 a	128.52 a
Swiss chard	RSG	40.00 a	66.67 a	40.00 a	60.00 a
	RRE	88.94 b	120.96 a	135.97 a	73.03 b
	GI	12.16 c	79.59 a	50.12 b	43.82 b
Tomato	RSG	105.56 a	83.33 b	103.70 a	94.44 ab
	RRE	91.26 a	82.32 a	75.23 a	73.94 a
	GI	71.56 ab	63.40 b	77.98 a	62.09 b

RSG = Relative Seed Germination; RRE = Relative Root Elongation; GI = Germination Index. * Different letters in a row indicate significant differences at $P < 0.05$.

There was a significant influence ($p < 0.05$) of treatments on the relative root elongation (RRE) of cabbage, onion, and Swiss chard; however, there was no significant influence of treatments on the RRE values of onion and tomato (Table 3). Across all vegetable species, the highest RRE value was observed in radish, recorded in the CM treatment with a value of 186.86%, while the lowest RRE value was observed in cabbage, recorded in the CM treatment with a value of 25.67% (Table 3). In cabbage, the RRE values ranged from 25.67% recorded in the control treatment to 67.67% recorded in the CM + F treatment (Table 3). In onions, the RRE values ranged from 44.28% in the CM + EM treatment to 76.64% in the CM + F + EM treatment (Table 3). The RRE in radish ranged from 13% in the CM + F group to 188.86% in the control treatment (Table 3). In Swiss chard, the highest RRE was recorded in the CM + F + EM treatment with a value of 135.97%, while the lowest was observed in the CM + EM treatment with a value of 73.03% (Table 3). In tomatoes, the highest RRE value of 91.26% was recorded in the CM treatment, while the lowest RRE value of 73.94% was observed in the CM + EM treatment (Table 3).

There was a significant influence ($p < 0.05$) of the treatments on the germination index (GI) for most tested vegetables, except for radish (Table 3). Across all the vegetable species, the highest GI was recorded in radish in the CM + F treatment with a GI value of 156.95, whereas the lowest GI value was observed in Swiss chard with a GI value of 12.1, observed in the CM treatment (Table 3). In cabbage, the lowest GI value of 16.90 was recorded in the control treatment, while the highest GI value of 60.46 was recorded in the CM + F treatment (Table 3). In onions, the GI values ranged from 29.38 to 76.88, with the lowest value recorded in the control and the highest in the CM + F + EM treatment (Table 3). In radish, the GI ranged from a value of 128.52 recorded in the CM + EM treatment to a value of 156.96 recorded in the CM + F treatment (Table 3). In Swiss chard, the highest GI was observed in the control with a value of 12.16, while the highest was recorded in CM + F with a GI value of 79.56 (Table 3). In tomato the GI value ranged from 62.09 recorded in the CM + EM treatment, to a GI value of 77.98 recorded in the CM + F + EM treatment (Table 3).

4. Discussion

4.1. pH and EC Response of Fly Ash and Effective Microorganisms Amended Camel Manure Vermicompost

The pH of vermicompost can be an indicator of microbial activity, nutrient transformation, and compost maturity [27]. The addition of fly ash to camel manure initially increased the pH and then subsequently reduced it, likely due to the natural biological acidification of organic matter during vermicomposting, which can counteract the typical alkaline properties of fly ash [28]. Enhanced nitrification during vermidegradation may also lower pH, especially when fly ash improves aeration and microbial activity [29]. Moreover, fly ash can immobilize basic cations through adsorption, chemical bonding, and physical encapsulation mechanisms, thereby reducing the pH in the vermicompost over time [30]. These findings align with previously reported results [31] that indicate that the addition of fly ash to cow manure promotes fulvic and humic acid formation, which then reduces the pH as the compost matures. The use of effective microorganisms resulted in pH reduction after week 12 as they could have accelerated the decomposition of camel manure, thereby producing organic acids such as lactic, acetic, and citric acids during rapid fermentation [32]. Additionally, effective microorganisms might speed up the nitrification process by releasing H^+ ions and lowering the pH of the final vermicompost [33]. Wang et al. [32] reported similar findings, indicating a gradual decrease in pH in EM-inoculated sewage sludge over time. Wang et al. [19] also reported similar trends in food waste vermicompost, highlighting the ability of EM to lower the pH of vermicompost.

The pH of the unamended camel manure remained stable throughout the vermicomposting period because of the natural buffering capacity of its existing carbonates and basic elements, such as Ca, Mg, Na, and K, which balanced organic acid formation during decomposition [34]. These findings contradict studies that reported pH reduction toward a neutral range during vermi-degradations of substrates such as food waste, cow manure, and goat manure [19,35]. These differences could be due to variation in the substrate used. Camel manure contains higher cellulose, hemicellulose, and lignin contents than other manure, resulting in a slow decomposition rate, which may resist rapid decomposition and pH alterations [36]. The findings imply that the camel manure-based vermicompost across all treatments fell within the pH ranges for mature vermicompost and the range of 6.0 to 8.5 that was previously reported [31], for suitable and crop growth-promoting vermicompost in most soils. The EM-inoculated vermicompost exhibited near-neutral pH, which is preferred by most crops, making it more suitable for a wide range of vegetable production [37]. Fly ash-amended vermicompost may be suitable as a buffering material in acidic soils [38], and its use in integration with other soilless substrates of lower pH, such as peat, may help to buffer its pH and enhance its agronomic use [39].

Electrical conductivity (EC) is a key indicator of soluble salt concentration in vermicompost [40]. In this study, EC showed increased values after 12 weeks of vermicomposting in the control, CM + F, and CM + EM treatments. The increase in unamended camel manure vermicompost reflects the mineralization of organic nitrogen solubilization and the release of base cations such as K^+, Mg^{2+}, and Ca^{2+} into the vermicompost matrix during vermi-degradation. This is consistent with the findings from other researchers [40]. The use of effective microorganisms may have sped up the process of mineralizing organic matter, which would have released more soluble nutrients and salts [19]. This would have led to a higher EC than the control, which is what Wang et al. [19] found for sewage sludge. The EC in the CM + F treatment went up because fly ash adds more soluble minerals and alkaline salts that dissolve during composting and raise the concentration of ions in the compost matrix (Table 1). This trend observed in the CM + F treatment in our study is inconsistent with the findings of Muniraj et al. [31], who reported that the EC in fly

ash-amended cow manure vermicompost decreased over time, reflecting the variability in substrate performance. In the CM + F + EM treatment, EC likely decreased because EM accelerated humic acid formation, increased cation exchange capacity [41], whereas fly ash promoted salt adsorption or precipitation, together reducing the concentration of soluble ions and lowering EC [30]. The decreasing trend in the electrical conductivity of vermicompost over time aligns with the findings of Muniraj et al. [31].

After 12 weeks, vermicompost EC ranged from 4.28 to 7.41 mS/cm, exceeding the recommended 4 dS/m threshold for most vegetable crops [42], indicating the need for salt-reduction pre-treatments before soil application. Our EC values were higher than those reported by Alsmadi et al. [7], who found that camel manure aerobically composted for 40 days had EC values below 1.8 mS/cm, highlighting the influence of composting duration and processing method on the final electrical conductivity. However, the EC ranges observed in our study are lower than the EC values of up to 11.23 mS/cm reported by Mupambwa et al. [25] for biochar-amended cow manure vermicompost, which highlights the substrate-specific influence on EC levels. The CM + F + EM treatment exhibited the lowest EC (4.28 mS/cm) and may therefore be more suitable for soil application, particularly in the cultivation of salt-tolerant species, as the reduced EC indicates a lower risk of salinity stress [42]. Although EC values exceeded the commonly recommended threshold for salt-sensitive crops, practical field management strategies such as controlled pre-leaching, reduced application rates, split applications, improved irrigation management, and crop selection can effectively mitigate potential salt stress under real-world agricultural conditions.

4.2. Macronutrients (N, P) in Fly Ash and Effective Microorganism-Amended Camel Manure Vermicompost

Nitrogen and phosphorus are among the most critical macro-elements for crop production, as they control vegetative growth, energy transfer, root development, and overall metabolic function [43]. The Olsen phosphorus concentration in the vermicompost increased after 12 weeks in the CM, CM + F, and CM + EM treatments. The increase in phosphorus content may be attributed to the enhanced mineralization of organic phosphorus by earthworm activity, together with the solubilization of inorganic phosphorus by phosphorus-solubilizing microorganisms [44]. The inclusion of effective microbial organisms resulted in a pronounced increase compared to the control and fly ash, likely due to the accelerated microbial activities by phosphate-solubilizing bacteria, consistent with the findings of Mupambwa et al. [17]. The fly ash amended treatment also had higher extractable P after 12 days compared to the control, which may be attributable to the higher Olsen P content of fly ash, as shown in Table 1. Comparable findings were reported by Muniraj et al. [31], who found that phosphorus in fly ash-amended cow dung vermicompost increased after 60 days. The consistently high Olsen P concentrations after 12 weeks of vermicomposting indicate that camel manure vermicompost is rich in phosphorus and has the potential to enhance crop establishment in P-deficient soils.

Ammonium nitrogen (NH_4-N) and nitrates/nitrites (NO_3-N) serve as immediate nitrogen sources for plants and as substrates for nitrifying microorganisms, and their dynamics reflect nitrogen mineralization [45]. The NH_4-N concentration increased over time in fly ash and effective microorganism-treated camel manure vermicompost, likely because of N-mineralization processes that release ammonium from organic matter [46]. This observation aligns with earlier studies that emphasize the role of earthworm activity and microbial mineralization in increasing nitrogen levels in vermicompost through their excretory products and rapid decomposition [47]. In contrast, in unamended manure, ammonium-N decreased, which could be due to ammonia volatilization during the initial stages of composting [48]. Ammonium volatilization may not occur in fly ash-amended vermicompost,

possibly because of the alkaline nature of fly ash (Table 1). The fly ash may have even buffered the pH, thereby reducing NH_3 losses, as reported by Taverne [49]. However, other studies have reported that high pH values, often associated with amendments such as fly ash, may also trigger ammonia volatilization, causing a reduction in the NH_4-N content [50]. Furthermore, the reduction in NH_4-N in unamended camel manure vermicompost can be attributed to the transformation of ammonia to nitrate by nitrifying bacteria [51]. In EM-inoculated vermicompost, EM-driven mineralization of N-rich compounds to NH_4-N could explain the higher retention of ammonium nitrogen in this treatment [52]. After 12 weeks, the fly ash-treated vermicompost retained the highest NH_4-N content compared with the control, highlighting that fly ash can effectively stabilize ammonium nitrogen and prevent its loss through volatilization or rapid nitrification [52]. Similar increasing trends over time in NH_4-N content were reported in vermicomposting systems by Feng et al. [53], while decreasing trends were also reported by Sonowal et al. [54]. Mature camel manure vermicompost, particularly with effective microbial treatment, retains high levels of ammonium nitrogen, indicating a stabilized nitrogen pool that can provide a sustained release of plant-available nitrogen [51,52]. This indicates that vermicompost with higher ammonium levels, such as CM + EM, can provide adequate nitrogen to crops. However, the risk of ammonium toxicity in the root zone requires careful monitoring to avoid phytotoxic effects [55].

The NO_3/NO_2-N concentration in camel manure also increased over time, particularly in the control and in the CM + F treatment. The progressive increase in NO_2/NO_3-N over time can be attributed to the microbial nitrification of ammonium released during organic matter mineralization, a process enhanced by earthworm activity and improved aeration during vermicomposting [56]. These results are similar to those of Katakula et al. [35], who found that the levels of NO_2/NO_3-N in goat manure-vegetable waste vermicompost went up until weeks 6–8 and then went down again by week 12. The results of Muniraj et al. [31] further supported this trend by reporting that, over time, the total organic matter content reduces due to enhanced conversion of organic elements to their inorganic forms. While increasing nitrate concentrations in treatments such as CM and CM + F indicates improved nitrogen availability for crops, they also suggest a higher potential for nitrate leaching if crop uptake is not well synchronized with nitrogen release [57]. The decrease in NO_2/NO_3-N after applying EM can be explained by the increased immobilization of mineral nitrogen by microbes and the partial suppression of nitrification due to higher heterotrophic microbial activity and organic acid production, as noted by Boruszko [58]. The findings of the present study are consistent with those of Vyas et al. [59], who reported a reduction in extractable NO_2/NO_3-N after effective microorganism inoculation in their vermicompost. In contrast, the findings do not align with those of Mupambwa et al. [17], who reported that the inclusion of EM in cow manure vermicompost increases the extractable nitrates in vermicompost, highlighting the unique responses of the substrates. Furthermore, the nitrate ranges (45.53–86.62 mg/kg) in our study after 12 weeks were higher than the nitrate ranges (<20 mg/kg) previously reported by Mupambwa et al. [17] for cow dung, highlighting that camel manure is richer in nitrogen and may serve as a good N source. This decreasing trend in vermicompost toward maturity may indicate better nitrogen retention in the CM + EM treatment, highlighting the reduced leaching risk from this amendment [60]. Overall, the findings highlight that camel manure can produce more stabilized vermicompost when inoculated with EM and that other treatments may pose a risk of N-losses due to faster N-releasing ability.

4.3. Trace Metals and Phytotoxicity of Fly Ash and Effective Microorganism-Amended Camel Manure Vermicompost

Heavy metal content monitoring in organic amendments is crucial because it influences both environmental safety and agricultural productivity, particularly when these amendments are applied to soils [61]. Some metals, such as Mn, Cu, Mo, and Co, are essential micronutrients for plant growth, but their elevated concentrations can result in phytotoxicity and accumulation in the food chain [62]. Other metals, such as Ni, As, and Pb, are non-essential and toxic, posing severe risks to both ecological systems and human health even at low concentrations, necessitating control and monitoring of trace metal levels prior to application [63]. In the present study, the concentrations of trace metals in camel manure vermicompost generally increased over time in most treatments, except for Pb and Mo in the CM + EM treatment, where reductions were observed. This finding is consistent with that of Gupta et al. [64], who reported that heavy metal concentrations in vermicompost may decrease or increase over time. According to Gupta et al. [62], heavy metal dynamics in vermicompost can be influenced by several mechanisms, including volume reduction, organic matter breakdown, the release of metals from organic complexes, and metal binding to humic substances. The rise in heavy metals during vermicomposting may be due to the mineralization of organic matter, which makes the vermicompost less bulky and raises the levels of heavy metals that don't break down [64]. Although mass reduction was not directly quantified gravimetrically, changes in C/N ratios and nitrogen dynamics indicate progressive organic matter mineralization during vermicomposting. The observed increase in total heavy metal concentrations is therefore likely attributable to a concentration-effect resulting from organic matter degradation and moisture loss rather than additional metal inputs. This observation aligns with previous studies that reported increased concentrations of Cd, Pb, Cr, and Ni in composting and vermicomposting processes due to substrate mass reduction [64]. In fly ash-treated vermicompost, the heavy metal concentrations could be more pronounced due to the elevated metallic composition of fly ash, as shown in Table 1.

However, the reduction in trace metals, such as Pb and Mo, under effective microorganism-treated vermicompost is likely due to the enhanced microbial activity facilitating metal immobilization or transformation into less bioavailable forms [65]. Other studies reported similar findings in EM-inoculated vermicompost, where EM addition led to decreased Mn and Fe concentrations [64]. The introduction of effective microorganisms has been reported to reduce lead, mercury, cadmium, and arsenic concentrations during composting, thereby mitigating the potential environmental risks associated with heavy metal accumulation [66]. Variations in the responses of different trace metals are attributable to their chemical properties, initial speciation, and interactions with organic matter and microbial communities [65]. According to the United States Environmental Protection Agency [67], the maximum allowable heavy metals in biosolids applied to soil are As 75 mg/kg, Cu 4300 mg/kg, Ni 420 mg/kg, Mo 75 mg/kg, and Pb 840 mg/kg. In our study, the measured heavy metal concentrations were below the established limits, indicating the safety and suitability of this vermicompost for agricultural applications [68]. CM-inoculated vermicompost, which reduces Pb and Mo levels, may be more beneficial for long-term soil health due to minimized risks [68]. It is important to note that this vermicompost has the potential to enrich soils with essential crop elements, such as Mn, Cu, Mn, and Mo [43], while maintaining non-essential metals within acceptable ranges. Though the total heavy metal concentrations observed in this study were perceived to be safe, it should be noted that this is context-specific and should be complemented by local or regional standards and bioavailable data.

Phytotoxicity testing of organic materials is crucial for assessing their maturity and suitability for agricultural applications, because immature composts can negatively impact seed germination and root growth [69]. The germination index (GI) is widely used to evaluate toxicity; therefore, it was used here as well to assess camel manure toxicity [70]. In the present study, different vegetables responded differently to treatments, indicating species-specific responses to various vermicompost amendments [69]. For example, certain species, such as radish, exhibited the highest germination index when cultivated in fly ash-amended vermicompost. In contrast, other species, such as Swiss chard, demonstrate reduced performance under the same conditions, suggesting varying sensitivities and requirements among different species [71]. For onions and cabbage, the control treatment gave the lowest GI values, while Swiss chard achieved the highest in this treatment, which can be explained by the intrinsic variability in seed sensitivity and tolerance to compost extracts across different plant species [72]. Camel vermicompost extract may reduce GI values in some species because of the presence of residual phytotoxic compounds or an imbalanced nutrient profile, similar to that reported for crop straw compost by Jagadabhi et al. [68]. The radish attained GI values exceeding 100, indicating phyto-stimulation of vermicompost extracts. These results align with those observed in agricultural byproduct-derived compost as reported by Thu and Loan [72]. The study by Milon et al. [73] also supports this finding that certain compost amendments can enhance seed germination and early plant growth.

A GI value below 50% signifies phytotoxicity, values ranging from 50% to 80% denote moderate toxicity, and values exceeding 80% indicate the absence of phytotoxicity [70]. In our study, GI values for most tested crops fell in the range of 50–80% or higher, suggesting that the vermicompost formulations generally exhibit moderate to no phytotoxicity, with some demonstrating phyto-stimulatory effects [72]. The high heavy metal content of this manure and fly ash, as shown in Table 1, can be the reason for the observed phytotoxicity or inconsistent germination indices across different plant species [74]. This finding, however, implies that camel manure may be safe for application to crops, but species selection is crucial because of varying sensitivities to compost extracts. Overall, the CM + F treatment may be more favorable in terms of phytotoxicity performance because most tested vegetables fall above 70% under this treatment. CM + EM treatment resulted in slightly lower GI values across the tested vegetables, rendering them less suitable; however, considering its beneficial properties, it remains a viable option. Although the vermicompost demonstrated overall agronomic potential, germination index (GI) values below the commonly accepted 80% maturity threshold suggest that certain treatments may require additional stabilization or dilution prior to direct application, particularly for sensitive seedlings. The lower germination indices observed in some treatments, despite favorable nutrient profiles, may be attributed to transient phytotoxic compounds produced during organic matter decomposition, including low-molecular-weight organic acids, phenolic compounds from lignin breakdown, and elevated ammonium concentrations, which are known to inhibit seed germination until further stabilization occurs. In the future, to optimize this vermicompost and ensure minimum toxicity, technologies such as biochar inclusion could be explored, as biochar can mitigate heavy metal toxicity and improve nutrient availability in composts [75].

5. Conclusions

The results of our study indicated that both CM + EM and CM + F possessed enhanced agronomic value; however, their optimal suitability differed according to the application objective. Although most chemical properties, including pH, EC, Olsen P, and mineral N forms, did not differ significantly between the two treatments, CM + EM exhibited the

highest Olsen P (398.71 mg/kg), NH_4-N (86.62 mg/kg) and NO_2/NO_3-N (111.93 mg/kg) concentrations, together with significantly reduced Pb and Mo contents, a lower pH (7.74) and an insignificantly higher EC (7.41 mS/cm), indicating superior nutrient status and greater agronomic potential for nutrient supply. Phytotoxicity bioassays revealed that CM + F produced higher germination index values (GI > 60) across most tested crops than CM + EM (cabbage, onion, and Swiss chard GI < 50). The CM + F treatment demonstrated lower phytotoxic effects and greater suitability for seed germination and early seedling establishment. While the vermicompost exhibited overall agronomic potential, germination index (GI) values below the commonly accepted 80% maturity threshold indicate that certain treatments may require additional stabilization or dilution before direct application, particularly when used for sensitive seedlings. Therefore, CM + EM is recommended as a soil amendment for established crops, where nutrient supply and metal safety are prioritized, whereas CM + F is recommended for nursery and seedling applications. Where CM + EM is intended for early growth stages, additional dilution or blending with mature substrates, accompanied by proper crop species selection, is recommended to minimize phytotoxicity risks. Overall, the findings indicate that vermicomposting camel manure with microbial inoculants significantly enhances nutrient enrichment, while fly ash amendments may contribute to mineral balance and buffering capacity. However, the variable phytotoxic responses suggest that additional maturation or blending with stabilizing amendments such as biochar may be necessary to optimize agronomic performance. These results highlight the potential of camel manure vermicomposting as a sustainable strategy for converting an underutilized organic resource into a value-added fertilizer for arid and semi-arid agricultural systems.

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