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Original Article

Evaluation of phytotoxic effects of integrated nutrient management techniques on soil nutrient availability and maize germination

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ABSTRACT

Nutrient management, which strategically combines two or more nutrient sources (organic, inorganic, and mineral amendments), aims to enhance crop resilience and sustain soil fertility under climatic variability. However, the early-stage phytotoxin effects and nutrient-release dynamics of different NM formulations require clarification for maize production systems in Nigeria. A laboratory bioassay was conducted using eight NM treatments: control (no amendment), cow dung (CD), NPK 15:15:15 fertiliser (NPK), agricultural lime (AL), and their combinations (CD+NPK, CD+AL, NPK+AL, CD+NPK+AL). Water extracts of each treatment (1:10 and 1:1 w/v) were incubated for 24 h at 25 ± 2 °C, centrifuged, and filtered before phytotoxicity testing with maize (Zea mays L.) seeds. Germination percentage, root and shoot length, and germination index (GI) were measured. Extract pH, EC, and nutrient composition were analysed. Data were subjected to one-way ANOVA, and means were separated with Tukey's HSD at $p \leq 0.05$. The extract pH ranged from 6.2 to 8.0. Single-mineral treatments (NPK, AL) exhibited moderate phytotoxicity (GI = 45–62%), while cow-dung-based combinations (CD+AL, CD+NPK, CD+NPK+AL) achieved higher GI ≥ 80%, indicating non-inhibition. The synergistic effect of organic inputs moderated extracted salinity and improved nutrient equilibrium. Enhanced early root vigour under combined CD-based treatments implies improved nutrient release and reduced osmotic stress. Combining cow dung with mineral fertilisers and lime effectively reduced phytotoxicity while improving nutrient balance, supporting precision and climate-smart integrated nutrient management adoption for maize systems in Nigeria.

KEYWORDS: *Aqueous extracts, Maize germination, Nutrient management, Organic amendments, Phytotoxicity*

INTRODUCTION

Nutrient application in agriculture is crucial for maintaining sustainable soil health, promoting crop growth, and minimising environmental impact. Excessive reliance on inorganic fertilisers often contributes to soil acidity, nutrient imbalance, and early-stage phytotoxicity (Mehdizadeh *et al.*, 2019). Conversely, organic amendments supply stable organic carbon, improve soil structure, and buffer ionic concentrations that promote seed germination, but they release their nutrients slowly during the developmental stage (Al-Suhaibani *et al.*, 2020). Integrated Nutrient Management (NM) offers a promising approach by combining organic and inorganic sources to optimise plant nutrition. However, NM constituents may possess phytotoxic or inhibitory properties, with the potential to negatively affect crops and soil quality. Understanding the phytotoxic potential of NM components is therefore essential for sustainable maize production systems.

Phytotoxicity testing is crucial for evaluating the impact of NM components on crops, soil quality, and the environment, as it provides a basis to pinpoint the potential for synergistic effects. Roccotiello *et al.* (2011) emphasise the role of phytotoxicity tests in affecting crop quality and production timelines. Thus,

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assessment of the phytotoxicity of soil amendments required a combination of chemical and biological methods (Luo *et al*., 2018). Bioassays, such as seed germination tests, are utilised to determine the phytotoxicity effects of amendments and their component. Luo *et al*. (2018) explained that these tests involve immersing seeds in aqueous extracts of amendments or growing plants in amended soil to assess phytotoxins. Also, Amarasinghe & Jayaweera (2022) reported that phytotoxicity assessment is mandatory as a parameter in the quality profiling of amendments such as compost and other soil amendments before utilising them. Many researchers have conducted diverse types of chemical analysis, as reported by Hase & Kawamura (2012) and Siles-Castellano *et al. (*2020). The focus of such studies has always been on identifying potential toxicants in soil amendments, such as organic products, NH^{4+}-N, heavy metals, and pesticide residues; many are impractical due to time, intensity, and expense (Roccotiello *et al*., 2011). However, Hase & Kawamura (2012) reported that the interactive effects of these toxicants cannot be evaluated properly through chemical analysis alone; therefore, calculating the germination index (GI) is a reliable method to ascertain the phytotoxic effect of amendments, and it evaluates the phytotoxins that can temporarily or permanently affect the growth of a plant. Thus, seed germination-related bioassays have been conducted as an effective, low-cost, and rapid method to determine phytotoxicity (Mazumder *et al.* 2020). Such seed germination experiments can be conducted by incubating selected seed varieties with aqueous extracts of amendments (Emino & Warman, 2004; Barral & Paradelo 2011). Many previous studies have followed seed germination protocols as a bioassay (Kebrom *et al.,* 2019). The seed germination index was introduced by Zucconi (1981) for cress seeds (*Lepidium sativum*, L.) by comparing seed radicle length and germination percentage to the control in deionised water.

Luo *et al*. (2018) emphasised the importance of bioassays in quantifying the phytotoxic and genotoxic effects of various substrates, thereby supporting the evaluation of soil amendment quality. The NM standard, entailing materials such as cow dung, NPK fertiliser, and agricultural lime, further highlights the need to understand how individual amendment components influence plant growth and soil health. Similarly, Kebrom *et al*. (2019) assessed the phytotoxicity of organic amendments, including chicken manure, milorganite, and dairy manure, on collard greens using seed germination bioassays combined with chemical analyses. Such investigations are important for determining how soil additives affect plant growth and development. Understanding how different amendments, individually or in combination, influence plant growth and soil health is necessary for informed nutrient management decisions; therefore, this study aims to evaluate the suitability of NM components for crop production and assess their potential impacts on soil quality.

MATERIALS AND METHOD

The Nutrient Management constituents of cow dung (CD), collected from confined cattle units and air-dried under ambient conditions to reduce excess moisture and stabilise the material before use, NPK fertiliser (NPK) and Agricultural lime (AL), procured from a certified agricultural input dealer, were used for the study. For experimental assessment, the individual components of the nutrient management (NM) system, namely CD, NPK, and AL, as well as their combinations, were prepared for phytotoxicity evaluation under controlled conditions. Each component was processed into an aqueous extract by mixing a measured quantity of the material with distilled water at a predetermined ratio, followed by agitation and filtration to obtain clear extracts suitable for bioassay analysis. These extracts were subsequently used to evaluate the potential effects of the NM constituents on crop growth and possible environmental implications. The extracts were also analysed for their soil nutrient quality enhancement components, such as amendment reaction (pH), organic carbon (Roccotiello *et al*., 2011), and electrical conductivity (EC) (Kebrom *et al.,* 2019). Phytotoxicity evaluation of these soil amendments involved both chemical and biological methods (Luo *et al*., 2018). The pH and electrical conductivity of the NM components and their combination were determined as described by Kebrom *et al.* (2019). The samples were centrifuged for 20 minutes at 10,000 g, and the supernatants were filtered through the Whatman No. 42 filter paper to obtain the first aqueous extracts of NM constituents. The extract was then diluted five times to obtain the second aqueous extract, while distilled water was used as a control.

Bioassay procedure for seed germination experiments

Ten maize seeds (*Zea mays*) were placed in 9-cm-diameter Petri dishes lined with Whatman filter paper No. 42. Five millilitres of aqueous extract were pipetted into each Petri dish, and Petri dishes with 5 mL distilled water only served as a control. Parafilm was used to seal each petri dish to prevent water loss while allowing air penetration. The Petri dishes were placed in a dark area (Fume cupboard) for seed germination and incubated at 25 °C. Each treatment in the study was replicated four times, and each treatment in the replicate was made up of ten seeds. The results were reported as means of the replicates. After 3 days, all the NM extracts (inorganic fertiliser NPK alone (NPK), organic manure-cow dung (CD), agricultural lime (AL), and their combinations (CD+NPK; NPK+AL; CD+AL; and CD+NPK+AL) and the control treated seed germination, root, and shoot length measurements were recorded. The whole experiment, including the preparation of fresh aqueous extracts and germination test, and the results were analysed by determining the relative seed germination (RSG), relative radicle growth (RRG), and germination index (GI) as shown below:

$$RSG = \frac{\text{Number of germinated seeds in aqueous extract}}{\text{Number of germinated seeds in distilled water (control)}} \text{ X } 100 \quad (1)$$

$$RRG = \frac{\text{Radicle length of germinated seeds in aqueous extract}}{\text{Radicle length of germinated seeds in distilled water (control)}} \text{ X } 100 \quad (2)$$

$$GI = \text{RSG/RRG} \quad \times 100 \quad (3)$$

Chemical analysis of organic fertilisers and soil amendments

The chemical properties and composition of the first and second aqueous extracts of NM constituents alone and in combinations were analysed using a pH meter (Accumet AB15), an electrical conductivity (EC) meter (Milwaukee MW 802), and a standardised procedure for analysing plant macro- and micro soil available nutrients. All reagents were analytical grade or better. The analysis was conducted on three independently prepared first and second aqueous extracts of each treatment as described above.

Statistical analysis

The number of germinated seeds and the average radicle length in each of the four biological replicates were determined. The RSG, RRG, and GI of each biological replicate were calculated using the formulas shown above in the seed bioassay section of the materials and methods. Data were subjected to one-way ANOVA using SPSS v25, which means separated with Tukey's HSD at $p \leq 0.05$. The results reported in this paper are the mean GI, RSG, and RRG of the four biological replicates, and the error bars are the standard error of the mean (SE) calculated using the equation $SE = SD/\sqrt{N}$, where SD is the standard deviation of the means, and N is the number of biological replicates.

RESULTS AND DISCUSSION

General Properties of NM Extracts

The chemical properties of the NM aqueous extracts varied across treatments, reflecting differences in acidity, salinity, organic matter content, and nutrient composition. The pH of the first and second extracts (1:1 and 1:10 dilutions) varied considerably across treatments (Table 1). The most alkaline conditions were recorded in treatments containing agricultural lime, particularly CD+AL (8.2 and 7.9) and CD+NPK+AL (8.4 and 8.1). Agricultural lime alone also produced alkaline extracts (8.1 and 7.8). In contrast, NPK alone consistently produced the most acidic extracts, with values of 5.2 and 5.9, respectively. These results confirm that lime application increases extract alkalinity, whereas mineral fertiliser reduces pH, creating more acidic conditions. Electrical conductivity (EC) ranged from 61.4 to 85.2 dS m^{-1} (Table 1), indicating differences in soluble salt concentrations among treatments. The highest EC values in both extracts were recorded in cow dung (CD) alone (85.2 and 82.5 dS m^{-1}), followed by CD+NPK+AL (83.6 and 82.0 dS m^{-1}), suggesting substantial ionic contributions from organic amendments. In contrast, the lowest EC occurred in NPK alone (66.2 and 61.4 dS m^{-1}), indicating comparatively lower soluble salt concentrations in the mineral fertiliser extracts. Lime-containing treatments generally showed moderate EC levels, reflecting intermediate ionic contributions. Organic carbon (OC) and organic matter (OM) were highest in CD+AL (OC = 2.78 mg kg^{-1}; OM = 4.78 mg kg^{-1}), indicating enhanced organic loading. Conversely, NPK alone recorded the lowest OC and OM values (OC = 1.02 mg kg^{-1}; OM = 1.75 mg kg^{-1}) because it contained no organic residues. Treatments containing cow dung consistently showed higher organic matter than inorganic-only treatments. Organic carbon is commonly associated with improved microbial activity, soil aggregation, and enhanced nutrient retention. Nutrient concentrations differed markedly among treatments. NPK alone contained the highest levels of potassium (6.42 mg kg^{-1}), phosphorus (21.52 cmol kg^{-1}), and nitrogen (1.96 cmol kg^{-1}), reflecting its concentrated nutrient composition. Agricultural lime treatments contained lower nutrient concentrations, including AL alone (K = 0.20 mg kg^{-1}; P = 6.02 cmol kg^{-1}; N = 0.35 cmol kg^{-1}). Cow dung-based treatments generally provided moderate nutrient levels, while combinations with NPK enhanced nutrient supply above that of cow dung alone. The carbon-to-nitrogen (C/N) ratio also varies across treatments. CD alone recorded the highest ratio (3.48), reflecting a greater proportion of carbon relative to nitrogen. The lowest ratio occurred in NPK alone (0.52), indicating concentrated mineral nitrogen with minimal carbon buffering. Combined treatments such as CD+NPK and CD+NPK+AL produced moderate C/N ratios (1.31–1.71), reflecting balanced organic and inorganic characteristics.

The chemical variability observed among NM extracts strongly influenced maize germination responses. The acidic nature of NPK-alone extracts was associated with reduced germination performance, supporting earlier reports that maize prefers slightly acidic to neutral conditions. Highly acidic extracts likely increased ion solubility to inhibitory levels, explaining the lower germination indices. Similar observations were reported by Sutriadi *et al*. (2022), who found reduced maize seedling performance under strongly acidic conditions. Gatew & Mengistu (2022) also demonstrated positive effects of cow dung-based amendments on maize germination and seedling development. Cow dung-based treatments showed relatively high EC values but still maintained favourable germination performance, suggesting that the organic matrix moderated ionic toxicity. This observation agrees with Li *et al*. (2000) and Sarwar *et al*. (2010), who reported that organic amendments reduce heavy metal bioavailability and phytotoxicity in crops. Improved germination at higher dilution (1:10) further confirmed that phytotoxic effects were concentration dependent. Organic matter likely enhanced ionic balance and microbial activity, thereby reducing toxicity. Although NPK alone contained the highest nutrient concentrations, it produced the most phytotoxic response. Excess soluble nutrients and ammoniacal nitrogen can inhibit seed germination and radicle growth. In contrast, organic-inorganic combinations such as CD+NPK and CD+AL improved buffering capacity and reduced toxicity. Agricultural lime also moderates acidity and supports favourable germination responses. These results support broader evidence that lime improves soil reaction, stabilises nutrients, and enhances early plant establishment. Lower C/N ratios in NPK-based treatments indicate rapid nutrient mineralisation but may increase short-term phytotoxic risk (Wang *et al*., 2020).

Table 1. General properties of NM material alone and in combination

COMP		CD	NPK	AL	CD +NPK	NPK +AL	CD +AL	CD+NPK +AL
pH(1:1)	1st Extract	8.2(0.06)	5.2(0.07)	8.1(0.26)	8.4(0.07)	7.2(0.20)	8.1(0.03)	8.4(0.06)
	2nd Extract	7.9(0.21)	5.9(0.15)	7.8(0.15)	8.1(0.08)	6.9(0.14)	7.7(0.30)	8.1(0.03)
EC(dS m^{-1})	1st Extract	85.2(0.03)	66.2(0.03)	80.6(0.06)	81.6(0.11)	74.5(0.02)	81.7(0.07)	83.6(0.11)
	2nd Extract	82.5(0.11)	61.4(0.05)	74.6(0.14)	79.6(0.13)	61.3(0.14)	80.6(0.05)	82.0(0.02)
TOC	mg/kg	3.62	1.02	1.72	2.74	2.03	2.78	2.74
TOM	mg/kg	6.23	1.75	2.96	4.71	2.12	4.78	4.75
K	mg/kg	2.49	6.42	0.20	7.47	7.13	2.41	4.37
P	cmol/kg	6.92	21.52	6.02	17.84	14.9	6.12	13.04
N	cmol/kg	2.04	1.96	0.35	1.87	0.37	2.12	1.61
C/N		3.48	0.52	1.81	1.46	0.90	1.31	1.71
Fe	cmol/kg	2.81	6.16	2.12	8.46	8.07	3.84	6.23
Mg	cmol/kg	0.76	2.16	0.11	4.5	3.72	1.36	3.17
Na	cmol/kg	0.48	1.43	0.04	2.62	2.34	2.16	1.35

COMP: Composition content, CD: Cow dung, NPK: Nitrogen-Phosphorus-Potassium fertilizer, AL: agricultural lime, pH: Composition reaction potential (acidity/alkalinity), TOC: Total Organic carbon, TOM: Total organic matter; K: Potassium, P: Phosphorus, N: Nitrogen, Fe: Iron, Mg: Magnesium, Na: Sodium, C/N: carbon-nitrogen ratio; EC: Electrical Conductivity; 1st extract= 1g of NM constituents alone and in combination to 10ml of distilled water, 2nd extract = 1ml of the aqueous extract to 10ml of distilled water

Phytotoxicity Effects NM on Maize Germination and Radicle Growth

Relative Seed Germination (RSG) and Relative Radicle Growth (RRG)

The germination bioassay demonstrated clear effects of the nutrient management constituents on seed germination and early root development, both widely used indicators of phytotoxicity in soil amendments. The control treatment recorded 100 percentage (%) relative seed germination (RSG) and relative radicle growth (RRG) at both dilutions, confirming favourable germination conditions without inhibitory substances. Similarly high RSG values were observed in agricultural lime (AL) (96 to 100 %), CD+AL (95 to 100 %), cow dung alone (91 to 96.7 %), and CD+NPK (93 to 85.9 %) as presented in Table 2. These results indicate that these treatments contained minimal phytotoxic compounds capable of inhibiting germination. In contrast, the lowest germination values occurred in NPK alone (61.1 to 56.7 %) and NPK+AL (58.3 to 60.7 %), indicating reduced germination performance under NPK-dominated extracts. The CD+NPK+AL treatment produced intermediate germination values ranging from 69.4 to 82.2 %. Overall, AL, CD, CD+AL, and CD+NPK maintained RSG values above 90 %, whereas NPK alone, NPK+AL, and CD+NPK+AL recorded the lowest RSG values, ranging from 58 to 70 %. Radicle growth followed a similar pattern. Seeds in the control treatment exhibited 100 % radicle elongation, while high RRG values were also recorded under AL (94 to 92 %), CD (92 to 90.9 %), CD+AL (99 to 96.6 %), and CD+NPK (96 to 93.4 %). The shortest radicle lengths occurred in NPK+AL (65.3 to 64.6 %) and NPK alone (63.7 to 58.1 %), confirming the inhibitory effect of highly concentrated mineral nutrient solutions on early root development. Longer radicles were associated with organic and lime-based treatments, while shorter radicles occurred in mineral fertiliser-dominated extracts.

From a phytotoxicity perspective, elevated electrical conductivity indicates higher concentrations of soluble salts that can impose osmotic stress on germinating seeds, potentially reducing water uptake and germination performance. Although cow dung treatments showed relatively high EC values, germination performance remained high, suggesting that the organic matrix moderated ionic toxicity. In practical agricultural systems, these materials are rarely applied as concentrated extracts; they are incorporated into soil where dilution, microbial decomposition, and soil buffering processes substantially reduce salinity effects. Consequently, the EC values primarily indicate amendment quality and management requirements rather than direct field salinity conditions. These observations indicate that organic amendments such as cow dung and lime-based treatments produced minimal phytotoxic effects, whereas mineral fertiliser-dominated treatments showed inhibitory stress. Similar findings were reported by Kebrom *et al*. (2019), who observed reduced germination and root growth under concentrated inorganic fertiliser extracts, while organic amendments maintained higher germination indices. Luo *et al*. (2018) also demonstrated the effectiveness of germination bioassays for detecting phytotoxic effects caused by soluble salts or toxic compounds. In many organic amendment studies, RSG values above 80 to 90 percentage indicate mature and non-phytotoxic materials. Therefore, the high RSG and RRG values observed in CD, AL, and CD-based treatments indicate low phytotoxicity and good suitability for agricultural use.

Table 2: Phytoinhibition effect of NM on maize seed germination and radicle elongation

TRT	RSG1	RSG2	RRG1	RRG2	pH (1:1)	EC (dS m^{-1})
CRTL	100.0^{a}	100.0^{a}	100.0^{a}	100.0^{ab}	7.00	20.35
AL	96.0^{a}	100.0^{a}	94.0^{ab}	92.0^{a}	8.16	77.71
NPK+AL	58.3^{c}	60.7^{c}	65.3^{d}	64.6^{c}	6.72	67.98
CD+NPK+AL	69.4^{bc}	82.2^{b}	65.9^{d}	82.9^{b}	8.30	82.87
CD+AL	95.0^{ab}	100.0^{a}	99.0^{ab}	96.6^{a}	8.07	81,21
NPK	61.1^{c}	56.7^{c}	63.7^{cd}	58.1^{c}	5.66	63.84
CD	91.0^{ab}	96.7^{ab}	92.0^{ab}	90.9^{ab}	8.19	85.42
CD+NPK	93.0^{ab}	85.9^{ab}	96.0^{bc}	93.4^{ab}	8.33	80.72

TRT-Treatments; CTRL -Control, AL -Agricultural Lime; NPK+AL -Agricultural Lime with NPK fertiliser; CD+NPK+AL -Agricultural Lime with NPK fertiliser with Cowdung; CD+AL -Agricultural Lime with Cowdung; NPK -NPK fertiliser; CD-Cowdung; CD+NPK -Cowdung with NPK fertiliser, RSG –. Relative seed germination, RRG –Relative radicle length. ***1*** *represent aqueous extract at 1:1 treatment dilution;* ***2*** *represent aqueous extract at 1:10 treatments dilution; EC-Electrical Conductivity*

Germination Index

The phytotoxicity effects of NM treatments on maize germination are summarised in Figure 1. Treatments differed significantly ($p \leq 0.05$) across germination and seedling vigour parameters. Among all treatments, NPK alone exhibited the strongest phytotoxic response, with RSG_1 = 61.1%, RSG_2 = 56.7%, and GI values of 48 – 46%, classifying it as extremely phytotoxic according to Emino and Warman (2004). The acidic pH of approximately 5.6 and the absence of organic matter likely created an ionic imbalance and osmotic stress, resulting in reduced germination and root elongation. The germination index trends corresponded closely with germination and radicle growth results. Highest GI values occurred in the control, CD+AL, CD, and CD+NPK treatments, while the lowest values consistently occurred in the NPK-only treatment, indicating severe phytotoxicity. Moderate GI values were recorded in NPK+AL and CD+NPK+AL, suggesting partial mitigation of mineral fertiliser toxicity when combined with lime or organic components. Based on GI classification, treatments were separated into three phytotoxicity groups. Non-phytotoxic treatments included CTRL, CD+NPK, CD+AL, AL, and CD, all with GI values above 85%. Mild phytotoxicity occurred in CD+NPK+AL and NPK+AL. Severe phytotoxicity occurred in NPK-alone, where GI remained below 50%. Extract dilution slightly improved GI in NPK-based treatments but had minimal influence on organic and lime treatments, confirming that organic and lime amendments are inherently less phytotoxic. Cow dung and cow-dung-based combinations maintained favourable pH, electrical conductivity, organic matter content, and biological indices. Agricultural lime increased extract alkalinity without negatively affecting germination. In contrast, NPK alone produced the most acidic extracts with the lowest organic matter and highest macronutrient concentrations, yet generated the strongest phytotoxic effects. The CD+NPK treatment significantly improved germination and radicle growth compared with NPK alone, confirming the buffering effect of organic matter. CD+NPK+AL also improved biological responses relative to NPK alone, although values remained lower than those observed in CD and AL treatments.

The germination index is a key bioassay indicator used to evaluate phytotoxicity because it integrates seed germination and root growth responses (Wang *et al*., 2020). According to Emino and Warman (2004), GI values below 50% indicate extreme phytotoxicity, values between 50 and 80% indicate moderate toxicity, and values above 80% represent non-phytotoxic materials. In this study, most treatments were classified as non-phytotoxic except the NPK extract. Similar findings have been reported by Sarwar *et al*. (2010) and Li *et al*. (2000), who showed that organic amendments such as manure and compost reduce heavy metal bioavailability and phytotoxic stress compared with mineral fertilisers. These results support the view that organic amendments provide a more sustainable approach to soil fertility management. Overall, integrating cow dung with mineral fertiliser improved germination performance, while NPK alone produced strong phytotoxicity due to acidity, high nutrient concentration, and lack of organic buffering.

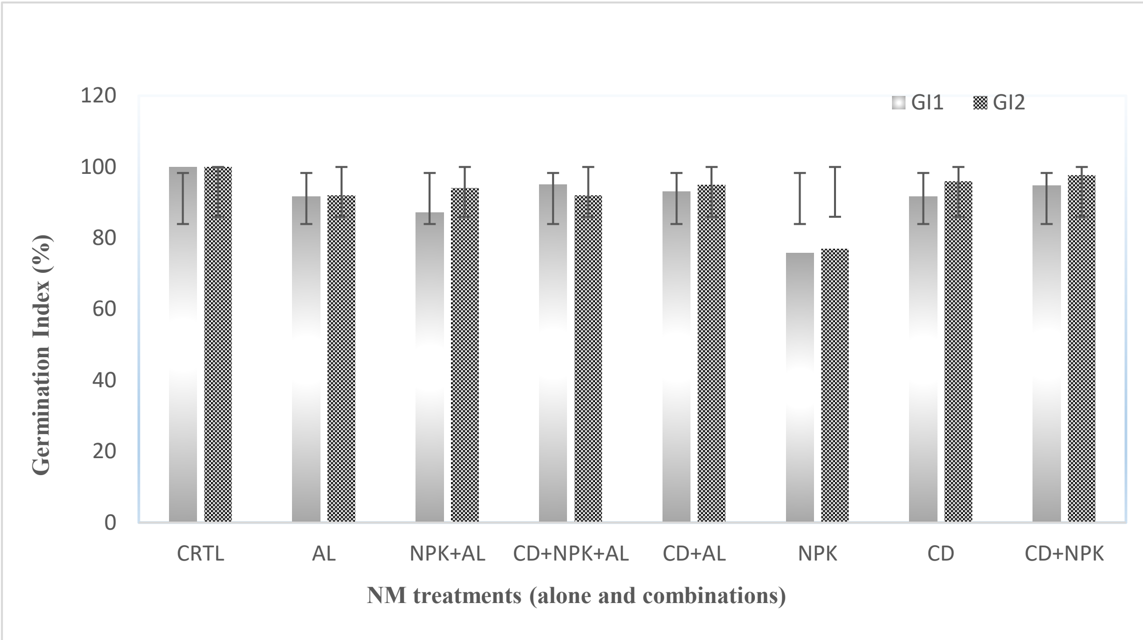

Figure 1. Germination Index (GI) of maize seed as influenced by aqueous extracts (1 and 2) of NM constituents and its combinations

NM constituents and its combinations: CTRL-control (distilled water), CTRL -Control, AL -Agricultural Lime; NPK+AL -Agricultural Lime with NPK fertilizer; CD+NPK+AL -Agricultural Lime with NPK fertilizer with Cowdung; CD+AL -Agricultural Lime with Cowdung; NPK -NPK fertilizer; CD-Cowdung; CD+NPK -Cowdung with NPK fertilizer, G1 and G2 = germination index for aqueous extracts of the TRTs' 1 and 2 respectively

CONCLUSION AND RECOMMENDATIONS

This study demonstrates that sole NPK extracts exert the highest phytotoxicity effects on maize germination due to elevated ionic strength and nutrient imbalance. Organic amendments, especially those combined with lime, significantly reduce phytotoxicity or Phytotoxicity and enhance early root development. Overall, the evidence indicates that integrated nutrient management strategies combining organic and liming materials promote optimal germination conditions for maize. In contrast, reliance on NPK-alone poses significant risks of phytotoxicity during early growth stages. The synergistic benefits of combining CD with NPK or AL demonstrate the value of integrated approaches that enhance chemical stability and reduce seedling stress. Integrated nutrient combinations should therefore prioritise organic-based inputs to support sustainable maize production. Field validation trials are recommended to optimise application rates and examine long-term soil health outcomes.

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Authors' Contributions

The Author managed data collection, interpretation of data, writing of the manuscript, material support, and review of the manuscript.

Ethical Statement

Not applicable.

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