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Effect of vermicompost, nitrogen and phosphorus on soil chemical properties, soybean and maize yields, and nutrients uptake in low and mid altitudes zones of Rwanda

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Abstract

Low soybean and maize yields in Rwanda are linked to declining soil fertility and poor fertilization practices. Integrating organic and mineral fertilizers may improve crop productivity and sustainability in low-input farming systems. This study evaluated the effects of vermicompost (V), nitrogen (N), and phosphorus(P) on soil properties, soybean and maize yields, and nutrient uptake in low-altitude Nyagatare and mid-altitude Tonga over two growing seasons (September 2022- July 2023). Soybean was grown during the first season, followed by maize in the second, using a randomized complete block design with triplicates. Treatments comprised vermicompost at 0, 3.5, and 7 t ha^{-1}; nitrogen at 0, 18, and 27 kg ha^{-1} for soybean, and 0, 64, and 96 kg ha^{-1} for maize; and phosphorus at 0, 46, and 69 kg P_2O_5 ha^{-1}. Combining the highest rates of vermicompost and mineral fertilizers increased soil organic carbon (OC), exchangeable potassium (K^+), and pH in both locations. In Nyagatare, these parameters increased by

33.2%, 54.8%, and 8.7%, respectively, compared with 54.8%, 38.2%, and 6.8% in Tonga. Soybean and maize grain yield and potassium uptake also increased significantly. Overall, integrating vermicompost and mineral fertilizers improved soil fertility, crop productivity, and nutrient uptake, supporting sustainable soybean-Maize rotations in Rwanda.

Keywords: Organic fertilizer, soil fertility, crop yield, nutrient content

1. Introduction

Soybean and maize are staple food crops widely cultivated in Rwanda due to their nutritional and economic importance. Soybean is a major oilseed crop with approximately 40% protein content, making it a valuable source of food and animal feed [1]

The major constraint to the productivity of soybean and maize in Rwanda is poor soil fertility [2], which also contributes to poor crop quality. Current national average yields for soybean and maize in Rwanda are approximately 0.47 t ha^{-1} and 1.3 t ha^{-1}, respectively, which are well below their potential yields of 3.0 and 3.7 t ha^{-1} under improved management, respectively [3]. Continuous cultivation without fallow, poor crop rotation, and limited use of external inputs have contributed to severe soil degradation and declining fertility. Growing soybean in poor soil with low available phosphorus (P) leads to poor nitrogen fixation in soybean [4], resulting in yields lower than 0.5 t ha^{-1}. Therefore, the application of phosphorus fertilizer at the rates of 21-30 kg ha-^{1} resulted in a 48.2% increase in soybean yield in Malawi, Zambia and Mozambique [5]. Inorganic fertilizers are widely recognized as essential inputs in agricultural systems, as they efficiently replenish nutrients depleted from soil during crop growth, grain development, and oil seed formation [6]. However, its continuous utilization has adverse effects on soil health, reduces productivity, and leads to nutrient loss due to soil organic carbon loss and intensified soil acidification, which results in poor soil fertility.

In depleted soils widely found in Rwanda, soybean crops fix less than 5 kg N ha^{-1} [5], which significantly reduces crop yields. In addition, more than 80% of Rwanda's arable land is nitrogen-deficient, which significantly reduces crop yields, particularly for

nitrogen-demanding crops like maize. Therefore, there is an urgent need to restore soil fertility in Rwanda through application of fertilizers and soil amendments to sustainably improve crop yields and quality. The long-term use of inorganic fertilizers alone can lead to soil nutrient imbalances when not informed with soil testing. Nutrient imbalances negatively impact ecosystems, reduce microbial populations and diversity, and ultimately decrease crop yields. Conversely, blending organic with inorganic fertilizers can reduce dependence on chemical inputs while enhancing soil ecological processes and agricultural productivity [6]. A long term experiment by Tian X et al.(2025) in a rapeseed-maize system demonstrated that integrated application of organic and inorganic fertilizers enhanced soil organic carbon, nutrient availability (phosphorus and potassium), soil structure, and crop yield relative to chemical fertilizer alone. Unlike many other organic fertilizers, vermicompost is distinguished by its stable granular texture, with diverse range of amino acids, enzymes. Vermicompost fertilization improves soil pH, water retention capacity, enhances microbial activity, macronutrient uptake, and boosts crop yield by 21.31%, and nutritional quality of the crop as well, compared to chemical fertilization [10,11]. Vermicompost stimulates beneficial microbial activity, releases naturally occurring growth-promoting compounds, and humic substances [7]. Furthermore, vermicompost boosts phosphorus-solubilizing microbes in the soil, gradually restoring and maintaining soil health [7]. Other documented benefits of vermicompost include improved soil physical properties such as aeration, drainage, and enhanced nutrient cycling [8]. Studies have shown that combining high rates of vermicompost with inorganic fertilizers improves soil pH in acidic soils and increases cation exchange capacity [9,10]. Furthermore, Li et al. [11] reported a positive effect of vermicompost rates integrated with inorganic fertilizers on soil properties, yield, and quality of watermelon in Zhejiang Province, China. Similarly, Vermicompost has been tested on soybean crops in north Iran and Kenya [12,13], and reported an increase in soybean growth, grain yield, and yield components.

Vermicompost in combination with nitrogen and phosphorus fertilizers significantly impacted maize growth and grain yield [14]. Furthermore, maize straw yield and grain nutrient content were higher when vermicompost was applied combined with biofertilizer than in the plots without amendments [15]. In Northern China, vermicompost was reported to improve soil total nitrogen (TN) by 59.2%, and soil organic carbon (OC) by

110.6% compared to non-fertilized plots [16]. Moreover, application of 100% of the recommended phosphorus through vermicompost resulted in significantly higher soil organic carbon, total nitrogen, available phosphorus, and exchangeable potassium compared to the full recommended dose of phosphorus chemical fertilizer [22]. Integrating farmyard manure with inorganic fertilizers has been reported to significantly improve soil fertility, soybean and maize, and nutrient uptake in Musanze and Bugesera districts; Rwanda [17]. Although farmyard manure gives good results when integrated with inorganic fertilizers, it is challenged by its low availability and accessibility. Given these limitations of traditional organic inputs, vermicompost can emerge as a promising alternative organic input source.

Vermicompost is an organic fertilizer resulting from a biological process of converting biodegradable waste into nutrient-rich manure by the action of earthworms [18]. The vermicomposting provides dual benefits: waste management and soil amendment. Despite its benefits, the combined use of vermicompost with nitrogen and phosphorus fertilizers has not been adequately explored on soil fertility and soybean and maize rotations in Rwanda. We hypothesized that vermicompost, either applied alone or in combination with nitrogen and phosphorus fertilizers enhance the soil chemical properties, yield, and nutrient uptake of soybean and maize crops. There was little information on the effect of vermicompost nitrogen and phosphorus on soil fertility and soybean and maize productivity, and crop nutrient uptake in a short rotational system. Therefore, the overall objective of this study was to evaluate the effects of vermicompost, nitrogen and phosphorus fertilizers on multiple response variables of soil properties, nutrients, and crop yield. Moreover, the specific objectives of this study were to i) evaluate the changes in soil nutrient content due to application of vermicompost, nitrogen and phosphorus fertilizer rates, ii) determine the effect of vermicompost, nitrogen and phosphorus fertilizer rates on soybean and crop yield and nutrient uptake.

2. Materials and methods

2.1 Description of experimental sites

The study was conducted in the low and medium altitude areas of Nyagatare and Tonga, Rwanda. The field experiments were established at the farms of University of Rwanda and conducted in two consecutive cropping seasons from September 2022 and

March 2023. Nyagatare site is located at a latitude of 1°17’33.0” S and longitude of 30°18’48.2” E, with an altitude of 1513 m above sea level. During the year 2022, the mean annual rainfall was 396.8 mm, with minimum and maximum annual temperatures of 15.63 °C and 27.57 °C, respectively. In 2023, the mean annual rainfall was 323.97 mm, and the minimum and maximum mean annual temperatures 15.78 °C (minimum) and 28.23 °C , respectively [19]. The soil in Nyagatare is a *Humic Ferralsol* with loam texture (75% sand, silt 10.30%, clay 14.60%). Soils have a good bulk density and are slightly acidic (pH 6.12) (Table 1).

Tonga site is located at latitude of 2°35’ S, longitude 29°43’ E, with an altitude of 1700 m above sea level. In 2022, the average annual rainfall was 414.3 mm, with the mean annual minimum and maximum temperatures of 15.48 °C and 24.94 °C, respectively [19]. In 2023, the mean annual rainfall was 417.3 mm, and the minimum and maximum mean annual temperatures were 15.49 °C and 24.54 °C, respectively. Soil in Tonga is a *Haplic Ferralsol* with a sandy clay loam (65.3% sand, silt 8.90%, and 25.8% clay) texture [20].

The main crops cultivated in both study areas are maize, bean, soybean, banana, sweet potato, rice, and cassava, typically grown as monocultures or in short rotations, with or without irrigation. The previous crops grown before the experiment were sweet potato in Nyagatare and Cassava in Tonga site. Soils have medium bulk density and are very acidic (pH 4.96) (Table 1).

152 **Table 1: Chemical characteristics of the soil in the study sites prior trials**

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Chemical soil properties	**Study sites**				
	Nyagatare (low altitude)	**Rating**	**Tonga (medium altitude)**	**Rating**	**Rating sources**
Clay (%)	14.60	N/A	25.8	N/A	
Silt (%)	10.30		8.90		[20]
Sand (%)	75		65.3		[20]
Soil classification	*Humic Ferralsol*	N/A	*Haplic Ferralsol*	N/A	[20
Textural class	Sandy loam	N/A	Sand clay loam	N/A	[20]
Bulk density (g cm^{-3})	1.29	Good (<=1.3)	1.47	Moderate (1.3 – 1.55)	[22]
p^H- H_2O	6.12	Slightly acidic (5.3 – 6.4)	4.96	Very acidic (4.2 – 5.2)	[21]
Organic C (%)	2.39	Low (< 4)	0.82	Low (< 4)	[21]
Total N (%)	0.11	Low (< 0.2)	0.06	Low (< 0.2)	[21]
Available P (mg kg^{-1})	8.11	Low (< 15)	4.95	Low (< 15)	[21]
Exchangeable K ($cmol_c$ kg^{-1})	0.22	Medium (> 0.2)	0.13	Low (< 0.2)	[21]

Exchangeable Ca ($cmol_c$ kg^{-1})	4.08	Medium (> 4)	2.37	Low (< 4)	[21]
Exghangeable Mg ($cmol_c$ kg^{-1})	1.09	Medium (> 0.5)	0.46	Very low (< 0.5)	[21]
Cation Exchange capacity (CEC) ($cmol_c$ kg^{-1})	5.39	Low (5-15)	2.96	Very low (5-15)	[21]

154 N/A=not applicable

155 Sources: Results of soil testing by Authors

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159 **2.2 Fertilizers and test crops**

160 The vermicompost used in this study was prepared by mixing cow manure with bean
161 straw in 2:10 (cow manure: bean straw) ratio. The bean straw was allowed to pre-
162 decompose for three weeks before introducing 100 earthworms per square meter into
163 the composting pile. Water was regularly applied to maintain a humidity level above
164 60%, and the compost was matured over a period of three months. Upon completion,
165 the vermicompost contained 20.73% organic carbon (OC), 1.18% total nitrogen (TN),
166 and 11.76 mg kg^{-1} available phosphorus (available P), exchangeable potassium (K^+),
167 calcium (Ca^{2+}), magnesium (Mg^{2+}), and cation exchange capacity (CEC) were 0.33,
168 4.32, 1.56 $cmol_c$ kg^{-1}, and 6.21 $cmol_c$ kg^{-1}, respectively.

169 The chemical fertilizers used were urea (46-0-0) for nitrogen and triple super phosphate
170 (TSP 0-46-0) for phosphorus. The test crop varieties were RWSOY 20-5 for soybean
171 and RHM 1407 for maize. These varieties were chosen based on their adaptability to
172 the study locations and their relevance to local agricultural practices.

2.3 Experimental design and treatments

The experiment was laid out in both sites in a Randomized Complete Block Design (RCBD) with three replications. The field experiment with soil and crops data collection involved standard cultivation of common crops and did not require ethical clearance. Instead, the study protocol received approval from the Directorate of Postgraduate Studies, Research, and Technology Transfer and Consultancy (DPRTC) of Sokoine University of Agriculture, and the office of the Vice-Chancellor granted the official Research Clearance with reference number SUA/ADM/R.1/8/852. Treatments were arranged in a factorial pattern involving different combinations with three levels of vermicompost (V) (0, 3.5, and 7 t ha^{-1}) in both soybean and maize, and three levels of inorganic Nitrogen (N) fertilizer at (0, 18 and 27 kg N ha^{-1}) for soybean, and 0, 64, and 96 kg N ha^{-1} for maize, and three levels (0, 46 and 69 kg P_2O_5 ha^{-1}) of phosphorus (P) in both soybean and maize. The size of each experimental unit was 2.8 m x 3.0 m (8.4 m^2), with guard rows of 0.5 and 1.5 m separating adjacent plots to minimize border effects. Soybean plants were spaced at 40 cm by 10 cm, while maize plants were spaced at 70 cm by 30 cm. These arrangements resulted in plant populations of 250000 ha^{-1} and 23,809 ha^{-1} for soybean and maize, respectively.

The experiment was implemented in two seasons, season I from September 2022 to February 2023 and season II from March to July 2023. Each cropping season was analyzed independently to evaluate site-specific effects.

201 **Table 2: Treatment details**

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Treatment combinations	Treatments in soybean			Treatments in maize		
	Vermicompost, V (tons ha^{-1})	Nitrogen, N (kg ha^{-1})	Phosphorus, P_2O_5 (kg ha^{-1})	Vermicompost, V (tons ha^{-1})	Nitrogen, N (kg ha^{-1})	Phosphorus, P (kg ha^{-1})
V1N1P1	0	0	0	0	0	0
V1N1P2	0	0	46	0	0	46
V1N1P3	0	0	69	0	0	69
V1N2P1	0	18	0	0	64	0
V1N2P2	0	18	46	0	64	46
V1N2P3	0	18	69	0	64	69
V1N3P1	0	27	0	0	96	0
V1N3P2	0	27	46	0	96	46
V1N3P3	0	27	69	0	96	69
V2N1P1	3.5	0	0	3.5	0	0
V2N1P2	3.5	0	46	3.5	0	46
V2N1P3	3.5	0	69	3.5	0	69
V2N2P1	3.5	18	0	3.5	64	0
V2N2P2	3.5	18	46	3.5	64	46
V2N2P3	3.5	18	69	3.5	64	69
V2N3P1	3.5	27	0	3.5	96	0
V2N3P2	3.5	27	46	3.5	96	46
V2N3P3	3.5	27	69	3.5	96	69
V3N1P1	7	0	0	7	0	0
V3N1P2	7	0	46	7	0	46
V3N1P3	7	0	69	7	0	69
V3N2P1	7	18	0	7	64	0
V3N2P2	7	18	46	7	64	46
V3N2P3	7	18	69	7	64	69

V3N3P1	7	27	0	7	96	0
V3N3P2	7	27	46	7	96	46
V3N3P3	7	27	69	7	96	69

The indices 1, 2, and 3 in the column of treatment combinations stand for rates applied for each treatment, i.e vermicompost (V) (0, 3.5, and 7 t ha^{-1}) and P (P_2O_5) (0, 46, and 69 kg ha^{-1}) in both soybean and maize experiments, and N (nitrogen) 0, 18, and 27 kg ha^{-1}) in soybean, and N (0, 64, and 96 kg ha^{-1}) maize.

2.4 Soil sampling and analysis

Before the trial and soon after laying out the field experiment composite soil samples were collected at 0-30 cm depth from each site's block (replicate) to obtain baseline soil status. At harvesting time, composite soil samples were also collected at the depth of 0-30cm from each plot, in both cropping seasons to evaluate the residual effect of treatments. The soil samples were air-dried, and ground to pass through a 2 mm sieve and stored in polythene bags until further analysis. Soil texture was determined using hydrometer method [24], and textural class was determined as per USDA textural triangle. For bulk density determination, the undisturbed soil cores were collected and oven-dried at 105 ^oC to constant weight. Bulk density was then calculated by dividing the dry weight of each core sample by the volume of the core ring. Soil pH was measured in a 1:2.5 soil water solution using a glass electrode. Soil organic carbon (SOC) was determined by Walkley Black method, while total was determined by Kjeldahl method, and available Phosphorus was determined by Bray II method as described by Pal et al. [25] and Okalebo et al. [26]. Exchangeable bases were determined using ammonium acetate saturation method at neutral pH and exchangeable K+, Mg2+ and Ca2+ in the extract was determined by atomic absorption spectrophotometry [26]. The cation exchange capacity (CEC) was determined by distillation-titration method of saturated NH4 leached by KCl as described by Okalebo et al. [26].

2.5 Crop data collection and analysis

2.5.1 Soybean and maize yield collection

Yield parameters were collected at crop physiological maturity from two central rows on a surface area of 1.68 m^2 (1.4 m long and 1.2 m wide) at each plot. Soybean grain and straw yields per plot were determined by harvesting the net plot when all the pods were fully mature. Harvesting was done manually, and all above-ground biomass was harvested. The total fresh weight biomass of the subsamples was recorded at harvest, sun-dried, followed by oven drying at 65 °C for 48 hours to determine the dry biomass. Soybean grain yield was determined at harvest by recording fresh weight before sun-drying, followed by oven-drying at 65 °C for 48 hours, and the grain yield was adjusted at 12.5% moisture content following the procedure given by Chen et al. [27] and expressed in metric tons per hectare (t ha^{-1}). For maize crop, harvesting was done when maize cobs were completely dry, and the grain yield determination was the same as for soybean grain yield, but the moisture content was adjusted to 13%. The straw yield was recorded and expressed in metric tons per hectare (t ha^{-1}), and the harvest index (HI) was calculated.

$$GY\ (t\ ha^{-1}) = (GW/P) * 10000 * [(100-GMH)/(100-GMD)] \quad (1)$$

Where: GY, GW, PLS, GMH, and GMD are grain yield, grain weight at harvest, plot size harvested, grain moisture content at harvest time, and moisture content at drying at 12.5 and 13% for soybean and maize, respectively.

$$\text{Harvest Index (H.I)} = \text{Grain yield/Total biomass yield} \quad (2)$$

2.5.2 Nutrient uptake determination in soybean and maize crop

The grains and straw oven-dried sub samples were ground to obtain a fine powder. The powdery straw and grain samples were separately digested by the Kjeldahl method. The samples' digests were analyzed for nitrogen, phosphorus, and potassium content. Total nitrogen (%) in digests was determined by the distillation-titration method; phosphorus content (%) was determined by the colorimetric method using a spectrophotometer at 882 nm wavelength, after color development by the phosphomolybdenum blue complex method; and potassium content (%) was determined using flame atomic absorption spectrometry. The nutrient uptake from grains and straw was calculated by multiplying the N, P, and K content (%) with the dry matter grain yield and straw yield (kg ha^{-1}) as per Okalebo et al. [26].

2.6 Statistical analysis

Data collected were subjected to analysis of variance (ANOVA) procedure using R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www, R-project.org/. (ver. 4.4.3). A combined data from two sites were analyzed and Pillai statistical test was used to determine significant different across various dependent variables; to evaluate the effect of treatment factors on multiple dependent variables, and MANOVA was performed. This statistical model examined how vermicompost, nitrogen and phosphorus fertilizer rates and their interaction influenced multiple dependent of crop yield, soil properties and plant uptake. The post hoc analysis was performed to separate treatment means considering the fixed effects and random effects structure using the Duncan and CLD (compact letter display) in R emmeans package. Results were reported in pairwise comparisons between treatment means. The significance level was tested at the $P < 0.05$ probability level. All statistical analyses were performed using the R software package. Principal component analysis and heatmap analysis were performed to determine the correlation between multiple variables (yield, soil properties, and nutrient uptake), the variation in dimensionality within the dataset, and the influence of independent variables on the behavior of the observed results across the two sites.

3. Results

3.1 Soil properties as influenced by vermicompost, nitrogen, and phosphorus fertilizer rates and their interactions

During the first season, the interaction of vermicompost, nitrogen, and phosphorus (V x N x P) fertilizer rates significantly ($P < 0.05$) influenced soil organic carbon (OC) in both Nyagatare and Tonga sites. In Nyagatare, exchangeable calcium (Ca^{2+}) was affected by two-way interactions between vermicompost and nitrogen, vermicompost and phosphorus, and nitrogen and phosphorus, all with $P < 0.05$ (Table 1 in S1 file). Exchangeable (K^+) and soil OC were significantly influenced by three-way interaction in Nyagatare ($P < 0.05$) (Table 3, and Table 1 in S1 file), In Nyagatare, the highest (3.52% and 0.37 $cmol_c\ kg^{-1}$) mean values of soil OC and exchangeable K^+ were obtained at 7 t V: 27 kg N: 46 kg P_2O_5 ha^{-1} and 7 t V: 27 kg N: 69 kg P_2O_5 ha^{-1}, respectively, compared to the lowest (2.35% and 0.21 $cmol_c\ kg^{-1}$) from the control plots, while in Tonga, exchangeable K^+ was significantly influenced by the two-way interaction of vermicompost and nitrogen ($P < 0.05$) (Table 1 in S1 file). Available phosphorus (Available P) differed significantly in Nyagatare due to the main effect of nitrogen and phosphorus fertilizer rates ($P < 0.05$), In Tonga, the three-way interaction effects of vermicompost, nitrogen and phosphorus fertilizer rates had a significant effect ($P < 0.05$) on soil organic carbon, available P, exchangeable Ca^{2+}, and exchangeable Mg^{2+} (Table 1 in S1 file). The highest (1.97%, 15.93 mg kg^{-1}, 3.72 $cmol_c\ kg^{-1}$, and 1.29 $cmol_c\ kg^{-1}$) mean values of soil OC, available P, exchangeable $C^{2+,}$ and Mg^{2+} were obtained at 7 t V: 27 kg N: 69 kg P_2O_5 ha^{-1} for soil OC and exchangeable Mg^{2+} and at 7 t V: 27 kg N: 46 kg P_2O_5 ha^{-1} for available P and exchangeable Ca^{2+}, compared to the lowest (0.89%, 4.66 mg kg^{-1}, 2.32 $cmol_c\ kg^{-1}$ and 0.76 $cmol_c\ kg^{-1}$) from the control plots, respectively (Table 3).

Soil total nitrogen (TN) was not significantly affected by three-way interactions in either location. However, in Nyagatare, TN was significantly influenced by the two-way interaction of vermicompost and nitrogen, and nitrogen and phosphorus fertilizer rates, all at $P<0.05$ (Table 1 in S1 file). The highest (0.16%) mean value of soil TN was obtained at 7 t V: 27 kg N ha^{-1}, compared to the lowest (0.08%) from the control plots (Table 4). In Tonga, the main effect of vermicompost and nitrogen fertilizer rates ($P <$

0.05) significantly affected the soil TN (Table 1 in S1 file). Soil pH was not significantly affected by either the two-way interactions. Nevertheless, a significant effect of the main effect of vermicompost rates was recorded in both sites P < 0.05) (Table 1 in S1 file). The highest (6.35 and 5.12) mean values of soil pH were recorded from the plots that received 7 t of V ha^{-1} in Nyagatare and Tonga site, respectively, compared to the lowest (5.8 and 4.77) from the control (Table 7).

The highest (0.16%) mean value of soil TN of was recorded at 27 kg N: 69 kg P_2O_5 ha^{-1} in Nyagatare, compared to the lowest (0.1%) from the control plots. In Tonga, the main effects of vermicompost and nitrogen significantly (P < 0.05) affected soil TN (Table 1 in S1 file). The maximum (0.14%) mean value of soil TN was obtained at 7 t V ha^{-1}, whereas the minimum (0.11%) from the control plots (Table 7). Though, the interventions used significantly improved soil properties, however, there was a variability between the sites and the way the variables respond to the applied inputs were differ.

During the second season, the three-way interaction effects among vermicompost, nitrogen and phosphorus (V x N x P) did not significantly influence soil Ca^{2+} at Nyagatare site (P > 0.05), whereas a significant effect was observed at the Tonga site (P = 0.02184). At Nyagatare, Ca^{2+} was affected by two-way interaction of vermicompost and nitrogen (P = 0.00027), vermicompost and phosphorus P = 0.01088), and nitrogen and phosphorus (P = 0.00087) (Table 2 in S1 file). The maximum (6.34 $cmol_c$ kg^{-1} and 4.44 $cmol_c$ kg^{-1}) mean values of exchangeable Ca^{2+} were determined from the plots receiving 7 t V: 46 kg P_2O_5 ha^{-1} and 7 t V: 96 kg N: 46 kg P_2O_5 ha^{-1}, in Nyagatare and Tonga sites, respectively (Table 3 and 5). Soil OC was not significantly affected by the three-way interaction at either site. However, significant effects were found for the two-way interaction of vermicompost and nitrogen (P = 0.00031), vermicompost and phosphorus (P = 0.02461), and nitrogen and phosphorus (P = 0.01709) in Nyagatare. Similarly, in Tonga, all two-way interactions significantly affect soil OC (P < 0.0001). (P < 0.05). The highest (3.77% and 2.31%) mean values of soil OC were obtained from the plots treated with 7 t V: 69 kg P_2O_5 ha^{-1} at Nyagatare and Tonga, respectively, compared to the lowest (2.81% and 1.35%) from the control plots (Table 5). Soil exchangeable Mg^{2+} did not statistically differ with the three-way interaction effects in Nyagatare site, but was significantly influenced by the three-way interaction of vermicompost, nitrogen and phosphorus at Tonga (P = 0.00248). The maximum (1.73

350 $cmol_c\ kg^{-1}$) means value of soil exchangeable Mg^{2+} was found in plots that received 7 t
351 V: 64 kg N: 46 kg P_2O_5 ha^{-1}, which was on par with 3.5 t V: 96 kg N: 69 kg P_2O_5 ha^{-1}, 7 t
352 V: 64 kg N: 46 kg P_2O_5 ha^{-1} and 7 t V: 96 kg N: 69 kg P_2O_5 ha^{-1}, compared to the
353 minimum (0.77 $cmol_c\ kg^{-1}$) from the control plots (Table 1). In Nyagatare, only the
354 vermicompost rates had a significant effect on Mg^{2+} levels ($P < 0.0001$) (Table 2 in S1
355 file).

356 Soil pH showed no significant response to any three-way or two-way interaction in either
357 site. However, a significant increase was noted for vermicompost rates in both
358 Nyagatare and Tonga ($P < 0.0001$) (Table 2 in S1 file). The highest (of 6.5 and 5.19)
359 mean values of soil pH values were recorded from plots treated with 7 t V ha^{-1} at
360 Nyagatare and Tonga, respectively, compared to the lowest (5.7 and 4.78) from the
361 control plots. The soil available P and K^+ were not significantly affected by three- way
362 interaction, but by the interaction of vermicompost and nitrogen in both Nyagatare ($P <$
363 0.0001) and Tonga ($P = 0.00020$), and by vermicompost and phosphorus in Nyagatare
364 ($P = 0.00071$) (Table 2 in S1 file). The highest (24.1 mg kg^{-1} and 21.16 mg kg^{-1}) mean
365 values of available P were found in plots that received 7 t V: 46 kg P_2O_5 ha^{-1} and 7 t V:
366 69 kg P_2O_5 ha^{-1} at the Nyagatare and Tonga sites, respectively, whereas the lowest
367 (10.49 mg kg^{-1} and 8.35 mg kg^{-1}) mean values of available P were obtained from the
368 control plots. Furthermore, the maximum (0.42 $cmol_c\ kg^{-1}$ and 0.26 $cmol_c\ kg^{-1}$) mean
369 values of K^+ were observed in plots treated with 7 t V: 96 kg N ha^{-1} at Nyagatare and
370 Tonga, respectively, compared to the minimum (0.27 $cmol_c\ kg^{-1}$ and 0.14 $cmol_c\ kg^{-1}$)
371 from the control plots (Table 4). Soil TN showed no significant changes under three-way
372 interactions at either site. However, a significant effect was observed from the
373 interaction of vermicompost and nitrogen in Nyagatare ($P < 0.0001$), and the main effect
374 of vermicompost and nitrogen fertilizer rates at Tonga ($P< 0.0001$) (Table 2 in S1 file).
375 The maximum (0.2% and 0.19%) mean values of TN were recorded at 7 t V: 96 kg N
376 ha^{-1} in Nyagatare, and 7 t V ha^{-1} in Tonga, compared to the minimum (0.13% and
377 0.15%) from the control plots (Table 4 and 7). Although the interventions presented a
378 significant improvement in soil chemical properties, they responded differently due to
379 the variability between the sites.

380

383 **Table 3: Three-way interaction effects of vermicompost nitrogen and phosphorus fertilizer rates on soil OC, available**
384 **P, Exch. Ca, and Exch. Mg during the first and second seasons**

	Soil data 1st season						Soil data 2nd season	
Treatment	Nyagatare		Tonga				Tonga	
interactions (VNP)	OC	Exch. K	OC	Available P	Exch. Ca	Exch. Mg	Exch. Ca	Exch. Mg
V3N3P3	3.40^{ab}	0.37^{a}	1.97^{a}	15.45^{ab}	3.65^{ab}	1.29^{a}	4.35^{ab}	1.76^{a}
V3N2P3	3.36^{a-c}	0.32^{a-e}	1.69^{cd}	15.11^{ab}	3.51^{b-d}	1.23^{ab}	4.23^{a-c}	1.73^{a}
V3N3P2	3.52^{a}	0.34^{a-c}	1.87^{b}	15.93^{a}	3.72^{a}	1.27^{ab}	4.44^{a}	1.72^{a}
V3N2P2	2.96^{e-f}	0.33^{a-d}	1.61^{de}	14.57^{b-d}	3.15^{e-g}	1.25^{ab}	3.87^{c-f}	1.73^{a}
V2N3P3	3.27^{bc}	0.37^{ab}	1.92^{ab}	15.33^{ab}	3.59^{a-c}	1.26^{ab}	4.31ab	1.71^{a}
V2N3P2	3.39^{ab}	0.33^{a-d}	1.75^{c}	14.49^{b-d}	3.39^{c-e}	1.24^{ab}	4.11^{a-d}	1.65^{a}
V2N2P3	3.20^{cd}	0.31^{a-f}	1.53^{e-h}	14.73^{bc}	2.77^{hi}	1.12^{bc}	3.49^{gh}	1.52^{ab}
V2N2P2	2.94^{e-g}	0.31^{a-f}	1.59^{ef}	11.97^{e}	2.67^{jk}	1.22^{ab}	3.39^{hi}	1.73^{a}
V3N1P3	2.78^{g-i}	0.31^{a-f}	1.51^{f-i}	14.85^{bc}	3.07^{f-h}	1.24^{ab}	3.79^{d-g}	1.64^{a}
V3N3P1	3.28^{bc}	0.33^{a-d}	1.57^{e-g}	11.63^{e}	3.63^{a-c}	1.28^{ab}	4.35^{ab}	1.74^{a}
V3N1P2	2.98^{ef}	0.28^{c-h}	1.48^{g-i}	13.63^{d}	2.98^{f-i}	1.01^{cd}	3.7^{e-h}	1.29^{b-d}
V2N3P1	3.073^{de}	0.29^{c-h}	1.55^{e-g}	9.9^{gh}	3.33^{d-f}	1.21^{ab}	4.05^{b-e}	1.74^{a}
V3N2P1	2.91^{e-g}	0.27^{d-j}	1.53^{e-i}	8.78^{ij}	3.02^{f-h}	1.19^{ab}	3.74^{e-h}	1.64^{a}

V1N3P3	2.71^{h-j}	0.24^{g-j}	0.9^{l}	9.18^{h}	2.35^{k}	0.82^{ef}	3.06^{ij}	0.69^{e}
V3N1P1	2.85^{f-i}	0.23^{h-j}	1.44^{g-i}	8.69^{ij}	2.92^{g-i}	0.99^{cd}	3.64^{f-h}	1.23^{b-d}
V2N2P1	2.81^{f-i}	0.25^{f-}	1.49^{g-i}	8.19^{j}	2.83^{g-i}	1.19^{ab}	3.55^{f-h}	1.67^{a}
V2N1P2	2.89^{e-h}	0.26^{e-j}	1.36^{jk}	10.48^{fg}	2.8^{hi}	0.82^{ef}	3.52^{f-h}	1.11^{d}
V2N1P3	2.79^{f-i}	0.28^{c-h}	1.44^{ij}	13.96^{cd}	2.82^{g-i}	1.12^{a-c}	3.54^{f-h}	1.46^{a-c}
V1N2P3	2.48^{l}	0.22^{h-j}	0.88^{l}	11.02^{ef}	2.33^{k}	0.79^{e-g}	2.97^{j}	0.69^{e}
V1N3P2	2.51^{kl}	0.3^{b-g}	0.87^{l}	9.05^{h-j}	2.39^{k}	0.79^{e-g}	3.04^{ij}	0.64^{e}
V2N1P1	2.69^{i-k}	0.22^{h-j}	1.34^{k}	8.6^{ij}	2.76^{ij}	0.92^{de}	3.48^{gh}	1.19^{cd}
V1N3P1	2.82^{f-i}	0.21^{ij}	0.82^{lm}	5.67^{k}	2.46^{jk}	0.8^{ef}	2.9^{j}	0.72^{e}
V1N2P2	2.39^{l}	0.21^{ij}	0.82^{lm}	9.04^{h-j}	2.41^{k}	0.78^{e-g}	2.83^{j}	0.63^{e}
V1N2P1	2.42^{l}	0.22^{h-j}	0.88^{l}	5.01^{kl}	2.24^{k}	0.92^{de}	2.88^{j}	0.7^{e}
V1N1P2	2.52^{j-l}	0.21^{ij}	0.82^{lm}	9.46^{hi}	2.38^{k}	0.71^{fg}	2.82^{j}	1.11^{d}
V1N1P3	2.52^{j-l}	0.22^{h-j}	0.77^{m}	9.04^{h-j}	2.35^{k}	0.65^{g}	2.86^{j}	0.5^{e}
V1N1P1	2.35^{l}	0.21^{j}	0.89l	4.66^{l}	2.32^{k}	0.76^{e-g}	2.83^{j}	0.74^{e}
P value	**0.04715**	**0.00692**	**0.001**	**0.0001**	**0.0001**	**0.0283**	**0.02184**	**0.00248**

V: vermicompost, N: nitrogen, P: phosphorus (P_2O_5), VNP: interaction of vermicompost, nitrogen and phosphorus fertilizer, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), N (0, 18, and 27 kg ha^{-1} or 0, 64, and 96 kg ha^{-1}), and (P_2O_5), (0, 46, and 69 kg ha^{-1}), respectively, OC: organic carbon, Exch. Ca: exchangeable calcium (Ca^{2+}), Exch. Mg: exchangeable magnesium (Mg^{2+}), Exch. K: exchangeable potassium (K^{+}), available P: available phosphorus, *P* value: *P*-probability value.

Table 4: Two-way interaction effects of vermicompost and nitrogen fertilizer rates on soil OC, TN, Exch. Ca, Mg, and K during the first and second seasons

	Soil 1st season	Soil 2nd season					
Treatment interaction (VN)	Nyagatare	Nyagatare				Tonga	
	TN	TN	OC	Exch. Ca	Exch. K	Exch. K	OC
V3N3	0.16[a]	0.2[a]	3.78[a]	6.51[a]	0.42[a]	0.26[a]	2.29[ab]
V3N2	0.13[b-d]	0.18[a-c]	3.71[ab]	6.31[a]	0.38[bc]	0.23[bc]	2.32[a]
V3N1	0.12[b-d]	0.18[bc]	3.43[cd]	5.86[b]	0.34[de]	0.21[cd]	2.06[c]
V2N3	0.14[ab]	0.2[ab]	3.59[b]	6.35[a]	0.4[ab]	0.24[ab]	2.22[ab]
V2N2	0.13[b-d]	0.18[bc]	3.57[bc]	5.98[b]	0.37[cd]	0.21[cd]	2.2[b]
V2N1	0.11[de]	0.16[c]	3.31[d]	5.55[c]	0.33[e]	0.2[d]	1.94[c]
V1N3	0.14[b-d]	0.19[ab]	2.93[e]	4.91[d]	0.27[f]	0.15[e]	1.35[d]
V1N2	0.11[cd]	0.17[bc]	2.86[e]	4.84[de]	0.27[f]	0.14[e]	1.35[d]
V1N1	0.08e	0.13[d]	2.89[e]	4.65[e]	0.27[f]	0.14[e]	1.36[d]
P value	**0.0487**	**0.0302**	**0.0003**	**0.00027**	**0.0001**	**0.0002**	**0.0001**

V: vermicompost, N: nitrogen, VN: interaction of vermicompost and nitrogen fertilizer, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), N (0, 18, and 27 kg ha^{-1} or 0, 64, and 96 kg ha^{-1}), respectively, TN: total nitrogen, OC: organic carbon, Exch. Ca: exchangeable calcium (Ca^{2+}), Exch. K: exchangeable potassium (K^{+}), *P* value: *P*-probability value.

Table 5: Two-way interactions of vermicompost and phosphorus fertilizer rates on soil OC, available P and Exch. K during the first and second seasons

	Soil 2nd season				
Treatment interactions (VP)	Nyagatare			Tonga	
	OC	Available P	Exch. Ca	OC	Available P
V3P3	3.72^{ab}	23.91^{a}	6.35^{a}	2.31^{a}	21.16^{a}
V3P2	3.77^{a}	24.1^{a}	6.34^{a}	2.3^{a}	20.82^{ab}
V3P1	3.44^{c}	18.5^{b}	6^{b}	2.06^{b}	17.25^{c}
V2P3	3.59^{b}c	23.18^{a}	6.09^{b}	2.2^{a}	20.58^{ab}
V2P2	3.6^{b}	22.92^{a}	6.09^{b}	2.2^{a}	20.03^{b}
V2P1	3.28^{d}	18.01^{b}	5.7^{c}	1.96^{b}	16.33^{d}
V1P3	2.95^{e}	17.69^{b}	4.87^{d}	1.35^{c}	16.56^{cd}
V1P2	2.91^{e}	17.48^{b}	4.77^{d}	1.36^{c}	16.11^{d}
V1P1	2.81^{e}	10.49^{c}	4.76^{d}	1.35^{c}	8.35^{e}
P value	**0.02461**	**0.03679**	**0.01088**	**0.0001**	**0.0001**

V: vermicompost, P: phosphorus (P_2O_5), VP: interaction of vermicompost and phosphorus fertilizer, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), and (P_2O_5), (0, 46, and 69 kg ha^{-1}), respectively, OC: organic carbon, Available P: available phosphorus, Exch. Ca^{2+}: exchangeable calcium (Ca^{2+}), *P* value: *P*-probability value.

Table 6: Two-way interaction effects of nitrogen and phosphorus fertilizer rates on soil OC, TN, and Exch. Ca and Exch. Mg during first and second season

	Soil 1st season	Soil 2nd season			
Treatment interaction (NP)	Nyagatare	Nyagatare		Tonga	
	TN	OC	Exch. Ca	OC	Exch. Mg
N3P3	0.16^{a}	3.53^{a}	6^{ab}	2.08^{a}	1.39^{a}
N3P2	0.14^{ab}	3.58^{a}	6.1^{a}	2^{a}	1.32^{ab}
N3P1	0.13^{bc}	3.21^{b}	5.7^{c}	1.8^{b}	1.4^{a}
N2P3	0.12^{cd}	3.5^{a}	5.92^{a-c}	2.03^{a}	1.32^{ab}
N2P2	0.12^{b-d}	3.45^{a}	5.78^{bc}	2.05^{a}	1.37^{a}
N2P1	0.13^{b-d}	3.21^{b}	5.45^{d}	1.8^{b}	1.34^{ab}
N1P3	0.1^{d}	3.24^{b}	5.41^{d}	1.76^{b}	1.4^{a}
N1P2	0.1^{d}	3.27^{b}	5.33^{d}	1.83^{b}	0.98^{d}
N1P1	0.1^{d}	3.13^{b}	5.33^{d}	1.78^{b}	1.06^{cd}
P value	**0.00630**	**0.01709**	**0.000087**	**0.0001**	**0.00312**

N: nitrogen, P: phosphorus (P_2O_5), N:P: interaction of nitrogen and phosphorus fertilizer, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}) and (P_2O_5), (0, 46, and 69 kg ha^{-1}), respectively, OC: organic carbon, Exch. Ca^{2+}: exchangeable calcium (Ca^{2+}), Exch. Mg^{2+}: exchangeable magnesium (Mg^{2+}), *P* value: *probability* value.

Table 7. Main effects of vermicompost fertilizer rates on soil pH and TN during the first and second seasons

	Soil 1st			Soil 2nd season		
Main effect (V)	Nyagatare	Tonga		Nyagatare	Tonga	
	pH	pH	TN	pH	TN	pH
V3	6.35[a]	5.12[a]	0.14[a]	6.5[a]	0.19[a]	5.19[a]
V2	6.22[b]	5.08[b]	0.12[b]	6.3[b]	0.17[b]	5.13[b]
V1	5.8[c]	4.77[c]	0.11[c]	5.7[c]	0.15[c]	4.78[c]
P value	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**

V: vermicompost, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), respectively, TN: total nitrogen, pH: hydrogen potential, *P* value: *P*-probability value.

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449 **3.2 Crop yields and nutrient uptake as influenced by vermicompost, nitrogen, and**
450 **phosphorus fertilizer rates**

451 **3.2.1 Soybean yields and nutrient uptake**

452 The first season's showed that the three-way interaction of vermicompost, nitrogen, and
453 phosphorus fertilizer rates had a significant effect on soybean straw yield and HI in
454 Nyagatare (P = 0.03172 and P = 0.00266) and Tonga (P = 0.00004 and P = 0.0003),
455 but only on soybean grain yield in Tonga (P < 0.00009) (Table 3 in S1 file). However, no
456 significant three-way interactions were observed on soybean grain yield in Nyagatare;
457 significant effects were observed from the two-way interactions of vermicompost and
458 nitrogen (P = 0.02004), vermicompost and phosphorus (P = 0.04694), and nitrogen and
459 phosphorus (P = 0.00163) fertilizer rates (Table 3 in S1 file). The highest (3.52 t ha^{-1}
460 and 1.63 t ha^{-1}) mean values of soybean grain yield (GY) were recorded from the plots
461 that received 7 t V: 69kg P_2O_5 ha^{-1} in Nyagatare and 7 t V: 27 kg N: 46 kg P_2O_5 ha^{-1}
462 fertilizer rates in Tonga, while the lowest (1.77 t ha^{-1} and 0.74 t ha^{-1}) mean values were
463 obtained from the control plots (Table 8 and 9). While the highest (8.20 t ha^{-1} and 3.32 t
464 ha^{-1}) mean values of soybean straw yield (SY) were recorded from the plots that
465 received 7 t V: 27 kg N: 46 kg P_2O_5 ha^{-1} in both sites, compared to the (4.54 t ha^{-1} and
466 2.46 t ha^{-1}) from the control plots (Table 8).

467 The analysis of variance results showed that vermicompost, nitrogen, and phosphorus
468 fertilizer rates had a significant effect (P < 0.05) on the nutrient uptake in soybean grain
469 and straw at both sites (Table 4 in S1 file). In Nyagatare, there was no significant
470 interaction between vermicompost, nitrogen, and phosphorus fertilizers in any of the
471 tested nutrient uptakes. However, in Tonga, the interaction of vermicompost, nitrogen
472 and phosphorus had a significant effect on soybean grain nitrogen uptake (GNUP) (P =
473 0.00002) and soybean grain potassium uptake (GKUP) (P = 0.02763) (Table 4 in S1
474 file). The highest (186.3 kg ha^{-1} and 71.26 kg ha^{-1}) mean values of soybean grain
475 nitrogen uptake (GNUP) were obtained from the plots that received 7 t V ha^{-1} and 7 t V
476 27 kg N: 69 kg P_2O_5 ha^{-1} in Nyagatare and Tonga sites, respectively (Table 8 and 9). In
477 Nyagatare the interactions of vermicompost and nitrogen, vermicompost and
478 phosphorus, and nitrogen and phosphorus fertilizer rates had a significant effect (P <
479 0.05) on GPUP and grain GKUP (Table 4 in S1 file). Grain phosphorus uptake (GPUP)

480 was significantly affected by the interaction of vermicompost and phosphorus fertilizer
481 rates in Nyagatare (P = 0.02178) and Tonga (P = 0.04827), respectively (Table 4 in S1
482 file). The maximum (79.8 kg ha^{-1} and 21.82 kg ha^{-1}) soybean grain phosphorus uptake
483 (GPUP) was obtained from 7 t V: 69 kg P_2O_5 ha^{-1} in Nyagatare and from 7 t V: 46 kg
484 P_2O_5 ha^{-1} in Tonga site, while the minimum (38.4 kg ha^{-1} and 11.9 kg ha^{-1}) of soybean
485 grain phosphorus uptake (GPUP) was obtained from control plots (Table 9). The
486 highest (40.1 kg ha^{-1} and 20.6 kg ha^{-1}) mean values of soybean grain potassium uptake
487 (GKUP) were obtained from 7 t V: 46 kg P_2O_5 ha^{-1} and 18 kg N: 69 kg P_2O_5 ha^{-1} in
488 Nyagatare and Tonga sites, respectively (Table 9).

489 Soybean straw SNUP, SPUP, and SKUP differed significantly (P< 0.05) due to the main
490 effect of V, N, and P fertilizer rates in both sites. Soybean SNUP was not statistically
491 different (P > 0.05) due to the main effect of nitrogen fertilizer rates in Nyagatare and
492 due to the main effect of phosphorus rates in Tonga sites (Table 4 in S1 file).

493

494 **3.3 Maize yields and nutrient uptake**

495 During the second season, maize crop was grown, and the analysis of variance results
496 showed that maize grain yield was significantly affected by the three-way interaction of
497 vermicompost, nitrogen, and phosphorus fertilizer rates in Nyagatare (P = 0.00424) and
498 Tonga (P = 0.00045) sites (Table 3 in S1 file). Statistically, the highest (3.79 t ha^{-1} and
499 2.89 t ha^{-1}) mean values of maize (GY) were obtained from the plots that received the
500 highest rates of 7 t V: 96 kg N: 69 kg P_2O_5 ha^{-1} fertilizers, compared with the lowest
501 (2.91 t ha^{-1} and 1.37 t ha^{-1}) received from control plots in Nyagatare and Tonga,
502 respectively (Table 8). Maize straw yield (SY) and harvest index (HI) were significantly
503 affected by the main effects of vermicompost, nitrogen and phosphorus fertilizer rates in
504 both sites (Table 5). In Nyagatare, straw yield (SY) differed significantly due to the main
505 effects of vermicompost (P = 0.0001) and phosphorus (P = 0.00686) fertilizer rates,
506 while in Tonga site, the SY was not significantly affected by the main effects of
507 vermicompost fertilizer rates, but differed significantly among the main effects of
508 nitrogen (P < 0.0001) and phosphorus (P = 0.0001) fertilizer rates (Table 3 in S1 file).
509 Maize HI differed significantly (P = 0.03158 and P < 0.0001) among vermicompost rates
510 in Nyagatare and Tonga, respectively (Table 4 in S1 file). Moreover, in Tonga site, the

HI was also significantly different due to N (P = 0.00002) and P (P = 0.00703) (Table 4 in S1 file). The results of maize yield highlighted the significant effects of inputs applied to the maize yield variables, though, the response differed due to the variation between sites.

Results indicated that the interaction of nitrogen and phosphorus had a significant effect on GNUP (P = 0.01993) and GKUP (P = 0.00218) at the Nyagatare site. Furthermore, maize GKUP showed a significant difference (P = 0.02981) due to the interaction of vermicompost and nitrogen fertilizer rates in Nyagatare site (Table 4 in S1 file). The maximum (158.29 kg ha^{-1} and 36.29 kg ha^{-1}) mean values of maize grain nitrogen uptake (GNUP) and maize grain potassium uptake (GKUP) were obtained from 96 kg N: 69 kg P_2O_5 ha^{-1}, compared to the minimum (125.79 kg ha^{-1} and 28.82 kg ha^{-1}) from the control (Table 9). Moreover, the highest (36.2 kg ha-1) mean value of maize grain potassium uptake (GKUP) were obtained from 7 t V: 96 N kg ha^{-1} with similar results at 3.5 t V: 64 N kg ha^{-1}, compared to the lowest (25.3 kg ha^{-1}) from the control. The results of maize grain potassium uptake obtained from the two-way interaction of nitrogen and phosphorus were comparable to the those obtain from the interaction of vermicompost and nitrogen fertilizer rates (Table 9). In Tonga, maize GKUP were significantly affected (P = 0.00390) by the interactions of vermicompost and nitrogen, and nitrogen and phosphorus (P = 0.03793). Moreover, in Tonga, maize GNUP was significantly affected (P = 0.01136) by the interaction and of vermicompost and nitrogen fertilizer rates (Table 4 in S1 file). The highest (63.7 kg ha^{-1}) mean value of maize grain nitrogen uptake was obtained at 7 t V: 96 N kg ha^{-1}, with statistically similar results obtained at 7 t V: 64 N kg ha^{-1}, 3.5 t V: 96 N kg ha^{-1}, and 3.5 t V: 64 N kg ha^{-1}, compared to the lowest (16.5 kg ha^{-1}) from the control plots (Table 9). The three-way interaction of vermicompost, nitrogen, and phosphorus fertilizer rates significantly (P = 0.01676) affected SPUP only in Nyagatare, but did not affect all other nutrients in both sites (Table 8, Table 4 in S1 file).

Table 8: Three-way interaction effects of vermicompost nitrogen and phosphorus fertilizer rates on crop yield and nutrient uptake

	Soybean							Maize		
Treatment interactions (VNP)	Nyagatare		Tonga					Nyagatare		Tonga
	SY	HI	GY	SY	HI	GNUP	GKUP	GY	SPUP	GY
V3N3P3	8.2^{a}	0.5^{b-g}	1.62^{a}	3.32^{a}	0.45^{-c}	71.26^{a}	20.64^{a}	3.81^{a}	10.88^{a-c}	2.89^{a}
V3N2P3	7.05^{a-c}	0.55^{a-d}	1.56^{ab}	2.95^{-d}	0.52^{a}	59.44^{a-d}	19.77^{ab}	3.77^{ab}	9.11^{a-c}	2.85^{b}
V3N3P2	5.47^{c-g}	0.71^{a}	1.63^{a}	3.27^{ab}	0.50^{ab}	67.58^{ab}	19.35^{a-c}	3.65^{a-c}	13.53^{a-c}	2.86^{ab}
V3N2P2	7.69 ^{ab}	0.5^{b-g}	1.61^{a}	3.05^{-d}	0.52^{a}	51.62^{a-e}	18.33^{a-d}	3.75^{ab}	13.33^{a-c}	2.81^{a-c}
V2N3P3	7.03^{a-c}	0.51^{b-f}	1.45^{a-d}	3.31^{a}	0.43^{-c}	62.12^{a-c}	19.84^{ab}	375^{ab}	8.11^{a-c}	2.81^{a-c}
V2N3P2	6.25^{b-g}	0.59^{a-c}	1.49^{a-c}	3.03^{-d}	0.49^{a-c}	59.00^{a-d}	16.17^{a-f}	3.65^{b}	7.37^{a-c}	2.61^{c-e}
V2N2P3	5.92^{b-g}	0.63^{ab}	1.34^{-e}	3.05^{-d}	0.43^{a-c}	47.39^{a-f}	18.34^{a-d}	3.71^{ab}	15.05^{ab}	2.67^{bc}
V2N2P2	7.12^{a-c}	0.45^{b-h}	1.43^{-d}	3.05^{-d}	0.47^{a-c}	61.59^{a-c}	19.07^{a-c}	3.65^{b}	9.89^{a-c}	2.64^{cd}
V3N1P3	5.76^{c-g}	0.44^{c-i}	1.36^{b-e}	3.19^{a-c}	0.42^{a-c}	31.67^{d-h}	17.03^{a-e}	3.57^{a-c}	18.72^{a}	2.30^{f-i}
V3N3P1	6.63^{a-d}	0.44^{c-i}	1.25^{d-h}	3.07^{a-d}	0.40^{b-d}	52.15^{a-e}	16.44^{a-f}	3.65^{a-c}	2.11^{c}	2.39^{f-h}
V3N1P2	6.35^{a-f}	0.38^{d-i}	1.32^{c-f}	2.81^{c-g}	0.47a^{-c}	34.33^{c-h}	13.44^{d-h}	3.43^{-d}	8.83^{a-c}	2.01^{jk}
V2N3P1	5.4^{c-g}	0.52^{b-e}	1.24^{d-h}	2.97^{a-d}	0.41^{a-c}	40.41^{b-g}	13.41^{d-h}	3.59^{a-c}	7.82^{a-c}	1.92^{kl}
V3N2P1	6.43^{a-e}	0.4^{d-i}	1.26^{d-h}	3.16^{a-c}	0.39^{b-d}	51.76^{a-e}	18.58^{a-d}	3.79^{a}	13.73^{a-c}	2.46^{d-f}

V1N3P3	6.46^{a-d}	0.40^{d-i}	1.29^{c-g}	2.82^{d-f}	0.45^{a-c}	31.13^{d-h}	12.64^{e-i}	3.53^{a-c}	2.27^{c}	2.11^{i-k}
V3N1P1	5.11^{d-g}	0.43^{c-i}	1.21^{e-i}	2.81^{c-g}	0.43^{a-c}	18.75^{f-h}	11.17^{f-}	3.31^{b-e}	10.16^{a-c}	1.69^{mn}
V2N2P1	6.53^{a-d}	0.36^{e-i}	1.16^{e-j}	2.49^{e-h}	0.46^{a-c}	53.73^{a-e}	15.88^{a-f}	3.62^{a-c}	5.61^{bc}	2.40^{e-g}
V2N1P2	6.5^{a-d}	0.32^{hi}	1.25^{d-h}	2.70^{d-h}	0.46^{a-c}	26.60^{e-h}	11.99^{e-i}	3.43^{a-d}	16.7^{ab}	1.77^{lm}
V2N1P3	5.95^{b-g}	0.37^{e-i}	1.23^{d-i}	2.9^{a-e}	0.42^{a-c}	34.41^{c-h}	14.14^{c-h}	3.52^{a-c}	6.36^{bc}	2.19^{h-j}
V1N2P3	5.24^{c-g}	0.47^{b-h}	1.10^{f-j}	2.29^{h}	0.45^{-c}	35.69^{c-h}	14.80^{b-g}	2.82^{f}	8.84^{a-c}	2.24^{g-i}
V1N3P2	5.41^{c-g}	0.42^{c-i}	1.07^{g-j}	2.82^{b-f}	0.38^{cd}	33.24^{c-h}	10.00^{g-i}	2.87^{ef}	7.69^{a-c}	1.70^{mn}
V2N1P1	5.57^{c-g}	0.34^{g-i}	1.15^{e-j}	2.81^{c-f}	0.41^{b-d}	21.07^{f-h}	9.34^{g-i}	3.20^{c-f}	10.6^{a-c}	1.61^{mn}
V1N3P1	5.11^{d-g}	0.42^{d-i}	1.08^{g-j}	2.35^{gh}	0.46^{a-c}	29.17^{e-h}	9.17^{hi}	2.91^{ef}	10^{a-c}	1.57^{m-o}
V1N2P2	5.5^{c-g}	0.37^{e-i}	1.03^{h-j}	2.39^{f-g}	0.43^{a-c}	45.80^{a-f}	10.97^{f-i}	2.98^{d-f}	4.91^{bc}	2.01^{jk}
V1N2P1	4.41^{g}	0.40^{d-i}	1.08^{g-j}	239^{f-g}	0.45^{a-c}	35.09^{c-h}	13.11^{d-h}	2.89^{ef}	6.99^{a-c}	2.10^{i-k}
V1N1P2	4.48^{f-g}	0.37^{e-i}	1.01^{il}	2.32^{h}	0.43^{-c}	11.14^{h}	9.87^{g-i}	2.78^{f}	11.81^{a-c}	1.51^{no}
V1N1P3	4.82^{d-g}	0.34^{f-i}	0.97^{j}	2.26^{h}	0.43^{a-c}	22.46^{f-h}	12.18^{e-i}	2.83^{f}	15.56^{ab}	1.92^{kl}
V1N1P1	4.54^{e-g}	0.29^{i}	0.74^{k}	2.46^{e-h}	0.30^{d}	16.01^{gh}	7.23^{i}	2.91^{ef}	8.82^{a-c}	1.37^{o}
P value	0.03172	0.00266	0.00009	0.00004	0.00003	0.00002	0.02763	0.00424	0.019	0.00045

V: vermicompost, N: nitrogen, P: phosphorus (P_2O_5), VNP: interaction of vermicompost, nitrogen and phosphorus fertilizer, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), N (0, 18, and 27 kg ha^{-1} or 0, 64, and 96 kg ha^{-1}), and (P_2O_5), (0, 46, and 69 kg ha^{-1}), respectively, GY: grain yield, SY: straw yield, HI: harvest index, GNUP: grain nitrogen uptake, GPUP: grain phosphorus uptake, GKUP: grain potassium uptake, SPUP: straw phosphorus uptake, *P* value; *P*-probability value.

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548 **Table 9: Two-way interaction effects of vermicompost and nitrogen,**
549 **vermicompost and phosphorus, and nitrogen and phosphorus fertilizer rates on**
550 **soybean and maize yields and nutrient uptake**

	Soybean			Maize		
Treatment interactions (VN)	Nyagatare			Nyagatare	Tonga	
	GY	GPUP	GKUP	GKUP	GNUP	GKUP
V3N3	3.62^{a}	83.43^{a}	39.87^{a}	36.2^{a}	63.7^{a}	18.8^{a}
V3 N2	3.45^{ab}	78.6a^{b}	37.8^{ab}	37.3^{a}	54.3^{a}	18.9^{a}
V3N1	2.35^{c}	52.91^{c}	27.07^{c}	32.5^{b}	28.2^{bc}	13.9^{bc}
V2N3	3.38^{ab}	78.27^{ab}	36^{ab}	34.7^{ab}	54.2^{a}	16.5^{ab}
V2N2	3.1^{b}	69.55^{b}	33.93^{b}	35.6^{a}	53.8^{a}	17.8^{a}
V2N1	2.08^{c}	46.94^{c}	22.44^{cd}	31.7^{bc}	27.4^{bc}	11.8^{c-e}
V1N3	2.37^{c}	53.09^{c}	23.45^{cd}	29^{cd}	38.9^{b}	10.6^{de}
V1N2	2.11^{c}	45.44^{c}	21.19^{de}	26.6^{de}	31.2^{b}	13^{cd}
V1N1	1.57^{d}	34.15^{d}	16.12^{e}	25.3^{e}	16.5^{c}	9.8^{e}
P value	**0.02004**	**0.01513**	**0.03551**	**0.02981**	**0.01136**	**0.00390**

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	Soybean			
Treatment interactions (VP)	Nyagatare			Tonga
	GY	GKUP	GPUP	GPUP
V3P3	3.52^{a}	37.5^{ab}	78.3^{a}	21.3^{ab}
V3P2	3.36^{ab}	40.1^{a}	79.8^{a}	21.8^{a}
V3P1	2.55^{c}	33.3^{b}	67.7^{b}	16.1^{c}
V2P3	3.2^{ab}	27.2^{c}	56.9^{c}	19^{b}
V2P2	3^{b}	34.2^{b}	73.9^{ab}	19.1^{ab}
V2P1	2.36^{cd}	24.9^{cd}	53.2^{cd}	15.7^{c}

V1P3	2.26^{cd}	22.8^{c-e}	49.8^{cd}	14.5^{cd}
V1P2	2.02^{de}	20.4^{de}	44.5^{de}	13.5^{cd}
V1P1	1.77^{e}	17.6^{e}	38.4^{e}	11.9^{d}
P value	**0.04694**	**0.01197**	**0.02178**	**0.04827**

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	Soybean	Maize	
Treatment Interactions (NP)	Nyagatare	Nyagatare	
	GY	GNUP	GKUP
N3P3	3.46^{a}	158.29^{a}	36.29^{a}
N3P2	3.29a	143.23^{bc}	32.24^{bc}
N3P1	2.63^{bc}	141.96^{bc}	31.29^{b-d}
N2P3	3.38^{a}	144.53^{a-c}	32.93^{b}
N2P2	3.05^{ab}	149.95^{ab}	33.54^{ab}
N2P1	2.23^{cd}	146.72^{a-c}	33.02^{b}
N1P3	2.15^{d}	140.72^{b-d}	31.08^{b-d}
N1P2	2.04^{d}	131.81^{cd}	29.68^{cd}
N1P1	1.81^{d}	125.79^{d}	28.82^{d}
P value	**0.00163**	**0.01993**	**0.00218**

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554 V: vermicompost, N: nitrogen, P: phosphorus (P_2O_5), VN: interaction of vermicompost
555 and nitrogen fertilizer, VP: interaction of vermicompost and phosphorus, and NP:
556 interaction of nitrogen and phosphorus, the factor levels stand with indices 1, 2, and 3
557 for N (0, 18, and 27 kg ha^{-1} or 0, 64, and 96 kg ha^{-1}) and (P_2O_5), (0, 46, and 69 kg ha^{-1}),
558 respectively, GY: grain yield, GNUP: grain nitrogen uptake, GPUP: grain phosphorus
559 uptake, GKUP: grain potassium uptake, *P* value; *P*-probability value.
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3.4 Combined mean results of soil properties, crop yield and nutrient uptake as influenced by the three-way interaction of vermicompost, nitrogen and phosphorus fertilizer rates

The combined mean results from two sites indicated that the three-way interaction of vermicompost, nitrogen and phosphorus fertilizer rates significantly ($P < 0.05$) affected soil exchangeable Mg^{2+}, in first season and soil OC in second season, but no effect on all other soil properties in both seasons. In first season, the highest (1.29 $cmlo_c$ kg^{-1}) mean value of soil exchangeable Mg^{2+} was recorded from 7 t V: 27 kg N: 69 kg P_2O_5 ha^{-1}, compared to (0.76 $cmlo_c$ kg^{-1}) from the control plots. The maximum (3.16%) mean value of soil OC was obtained from 7 t V: 96 kg N: 69 kg P_2O_5 ha^{-1}, while the minimum (2.08%) was obtained from the control plots (Table 10). The three-way interaction effects of vermicompost, nitrogen and phosphorus significantly ($P = 0.0018$) affected soybean harvest index (HI), but no significant effect observed on other soybean yield and nutrient uptake variables. The highest (0.61) mean value of soybean harvest index was observed at 7 t V: 27 kg N: 46 kg P_2O_5 ha^{-1}, compared to the lowest (0.3) from the control plots (Table 10). The combined mean results from two sites showed that the tree way interaction of vermicompost nitrogen, and phosphorus fertilizer rates had only a significant effect ($P < 0.0294$) on maize straw phosphorus uptake. The maximum (15.58 kg ha^{-1}) mean value of maize straw phosphorus uptake (GPUP) was obtained at 7 t V: 0 kg N: 69 kg P_2O_5 ha^{-1}, compare to the minimum (6.22 kg ha^{-1}) from the control (Table 10).

3.5 Combined mean results of crop yield and nutrient uptake as influenced by the main effects of vermicompost, nitrogen and phosphorus fertilizer rates

The combined mean of soybean grain yield (GY), all grain nutrient uptake and straw nutrient uptake were significantly ($P < 0.01$) influenced by the three main effects of vermicompost, nitrogen and phosphorus fertilizer rates (Table 11), The highest (2.28 t ha^{-1}, 2.24 t ha^{-1} and 2.16 t ha^{-1}) mean values of soybean grain yield (GY) were obtained at 7 t V, 27 N kg and 69 P_2O_5 kg ha-1, respectively (Table 11). Conversely, the lowest mean values (1.53 t ha^{-1}, 1.57 t ha^{-1}, and 1.68 t ha^{-1}) were recorded in the control. The combined mean results were comparable among the three main fertilizer effects, and a

similar trend was observed in the soybean nutrient uptake variable (Table 11). Additionally, the maize straw yield was significantly ($P < 0.01$) influenced by all main effects of fertilizer rates (Table 11). The maximum (5.32 t ha^{-1}) mean maize straw yield (SY) was obtained from the plots that received 7 t V ha^{-1}, with similar mean results to those obtained at 3.5 t ha^{-1}; the combined mean results were comparable across the rest of the two main effects of nitrogen and phosphorus. Moreover, the maize grain phosphorus uptake (GPUP) and straw potassium uptake (SKUP) were significantly ($P < 0.01$) affected by the main effects of vermicompost, nitrogen and phosphorus fertilizer rates (Table 11). The highest mean value of grain phosphorus uptake (GPUP, 30.3 kg ha^{-1}) and straw potassium uptake (SKUP, 6.82 kg ha^{-1}) were recorded at 7 t V ha^{-1}. For maize straw potassium uptake, results at 7 t V ha-1 were statistically similar to those at 3.5 t V ha^{-1}, though both were significantly higher than the control. Furthermore, the results obtained from all vermicompost rates were comparable to the mean effects of nitrogen and phosphorus rates (Table 11).

Table 10: Three-way interaction effects of vermicompost nitrogen and phosphorus fertilizer rates on soil properties, crop yield and nutrient uptake as combined both sites

	Season 1	Season 2	Soybean	Maize
Treatment interactions (VNP)	Combined data	Combined data	Combined data	Combined data
	Exch. Mg	OC (%)	HI	SPUP
V3N3P3	1.29^{a}	3.16^{ab}	0.49^{b-d}	10.57^{a-d}
V3N2P3	1.23^{ab}	3.16^{ab}	0.54^{ab}	9.6^{a-d}
V3N3P2	1.27^{ab}	3.2^{a}	0.61^{a}	11.97^{a-c}
V3N2P2	1.25^{ab}	3.14^{a-c}	0.51^{b-c}	11.02^{a-d}
V2N3P3	1.26^{ab}	3.05^{b-d}	0.48^{b-e}	8.95^{a-d}

V2N3P2	1.24^{ab}	3.02^{cd}	0.54^{ab}	8.48^{a-d}
V2N2P3	1.12^{bc}	2.99^{d}	0.54^{ab}	12.33^{ab}
V2N2P2	1.22^{ab}	3.03^{cd}	0.46^{b-f}	9.12^{a-d}
V3N1P3	1.24^{ab}	2.74^{e}	0.43^{c-f}	14.58^{a}
V3N3P1	1.28^{ab}	2.77^{e}	0.42^{d-g}	5.95^{b-d}
V3N1P2	1.01^{cd}	2.78^{e}	0.43^{c-g}	8.44^{a-d}
V2N3P1	1.21^{ab}	2.66^{ef}	0.47^{b-f}	8.07^{b-d}
V3N2P1	1.19^{ab}	2.77^{e}	0.4^{e-g}	10.13^{a-d}
V1N3P3	0.82^{ef}	2.2^{g}	0.43^{c-g}	4.89^{d}
V3N1P1	0.99^{cd}	2.72^{e}	0.41^{d-g}	8.44^{a-d}
V2N2P1	1.19^{ab}	2.65^{ef}	0.4^{e-g}	6.58^{b-d}
V2N1P2	0.82^{ef}	2.67^{ef}	0.4^{e-g}	12^{a-c}
V2N1P3	1.12^{a-c}	2.66^{ef}	0.48^{b-e}	6.86^{b-d}
V1N2P3	0.79^{e-g}	2.16^{g}	0.41^{e-g}	7.22^{b-d}
V1N3P2	0.79^{e-g}	2.15^{g}	0.38^{g}	6.95^{b-d}
V2N1P1	0.92^{de}	2.57^{ef}	0.44^{c-g}	8.17^{b-d}
V1N3P1	0.8^{ef}	2.09^{g}	0.4^{e-g}	6.86^{b-d}
V1N2P2	0.78^{e-g}	2.08^{g}	0.43^{c-g}	5.73^{c-d}
V1N2P1	0.92^{de}	2.09^{g}	0.41^{e-g}	5.96^{b-d}
V1N1P2	0.71^{fg}	2.2^{g}	0.38^{fg}	7.85^{b-d}
V1N1P3	0.65^{g}	2.1^{g}	0.39^{fg}	11.74^{a-c}
V1N1P1	0.76^{e-g}	2.08^{g}	0.3^{h}	6.22^{b-d}
P value	**0.0283**	**0.0045**	**0.0018**	**0.0294**

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V: vermicompost, N: nitrogen, P: phosphorus (P_2O_5), VN: interaction of vermicompost and nitrogen fertilizer, VP: interaction of vermicompost and phosphorus, and N:P: interaction of nitrogen and phosphorus, the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), N (0, 18, and 27 kg ha^{-1} or 0, 64, and 96 kg ha^{-1}), and (P_2O_5), (0, 46, and 69 kg ha^{-1}), respectively, Exch. Mg: exchangeable Magnesium (Mg^{2+}), OC: soil organic carbon, HI: harvest index, SPUP: straw phosphorus uptake, *P* value; *P*-probability value.

Table 11: The main effects of nitrogen and phosphorus fertilizer rates on soybean and maize yields and nutrient uptake as combined in both sites

Main effect	Soybean yield and grain nutrient uptake						Maize straw yield and nutrient uptake		
V	GY	GNUP	GPUP	GKUP	SNUP	SPUP	SY	GPUP	SKUP
V1	1.53^{c}	77.75^{b}	28.77^{c}	15.6^{c}	24.35^{b}	15.58^{b}	4.8^{b}	18.92^{c}	5.07^{b}
V2	2.08^{b}	110.3^{a}	41.41^{b}	22.34^{b}	33.79^{a}	22.99^{a}	5.29^{a}	27.99^{b}	6.46^{a}
V3	2.28^{a}	118.41^{a}	45.69^{a}	25.36^{a}	35.42^{a}	24.69^{a}	5.32^{a}	30.3^{a}	6.82^{a}
***P* value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
N									
N1	1.57^{c}	80.13^{c}	29.73^{c}	17.18^{b}	27.75^{b}	18.05^{c}	4.85^{b}	21.96^{b}	5.58^{b}
N2	2.09^{b}	105.72^{b}	40.69^{b}	22.35^{a}	31.63^{a}	21.08^{b}	5.24^{a}	27.56^{a}	6.19^{a}
N3	2.24^{a}	120.43^{a}	45.45^{a}	23.78^{a}	34.18^{a}	24.13^{a}	5.32^{a}	27.71^{a}	6.58^{a}
***P* value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.0011**
P									
P1	1.68^{b}	86.58^{b}	32.03^{b}	17.72^{b}	27.36^{b}	18.27^{b}	4.85^{c}	21.22^{c}	5.09^{b}
P2	2.06^{a}	109.42^{a}	40.79^{a}	22.23^{a}	32.96^{a}	21.68^{a}	5.15^{b}	26.48^{b}	6.56^{a}
P3	2.16^{a}	110.28^{a}	43.04^{a}	23.37^{a}	33.25^{a}	23.32^{a}	5.41^{a}	29.52^{a}	6.71^{a}
***P* value**	**<0.001**	**0.0000**	**<0.001**	**<0.001**	**0.0007**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

V: vermicompost, N: nitrogen, P: phosphorus (P_2O_5), the factor levels stand with indices 1, 2, and 3 for (V) (0, 3.5, and 7 t ha^{-1}), N (0, 18, and 27 kg ha^{-1} or 0, 64, and 96 kg ha^{-1}), and (P_2O_5), (0, 46, and 69 kg ha^{-1}), respectively, GY: grain yield, SY: straw yield, GNUP: nitrogen uptake in grain, GPUP: phosphorus uptake in grain, GKUP: potassium uptake in grain, SNUP: nitrogen uptake in straw grain, SPUP: Phosphorus uptake in straw, SKUP: potassium uptake in straw, *P* value: *P*-probability value.

3.6 Multivariate analysis

The MANOVA table provides a multivariate test of treatment factors effects on a set of response variables of soil properties, soybean and maize yield and nutrient uptake (Table 5 and 6 in S1). The replication showed variability due to microvariation in soil conditions. The analysis indicates a strong significant difference from two sites to the combined response variables mainly due to the application of vermicompost, nitrogen and phosphorus fertilizer rates and probably due to other factors such as edaphoclimatic conditions. It has been observed that the vermicompost fertilizer rates influences the whole parameters of soil properties, soybean and maize yield and nutrient uptake. Therefore, the higher significant effect was also observed from the main effect of vermicompost, nitrogen and vermicompost fertilizer rates. while the weaker significant effect was observed from three-way interactions effects of vermicompost, nitrogen and phosphorus fertilizer rates as well the interaction towards the studied variables (Table 5 and 6 in S1).

3.7 Overall variability of soybean-maize yield, soil properties, and nutrient uptake

A principal component analysis was performed to determine the correlation between multiple variables, dimensional variation in the data set, and the influence of independent variables on the behavior of the observed results within two different sites of the study (Figs 1 and 2). For the first season soybean crop, the first two principal components explained 74.8% and 9.1% of the total variance. Points representing each

experimental unit were clustered by site but not clearly by any of the fertilizer treatments. Parameters such as crop yield, soil chemical properties, and nutrient uptake exhibited similar trends across both sites, with most variables loading strongly on Dim1. Moreover, considering the vectors' direction and length, all variables showed a significant positive correlation *(*$P < 0.05$) with each other and were significantly influenced by the vermicompost, nitrogen, and phosphorus fertilizer rates in Nyagatare and Tonga. However, slightly higher variability was observed among the measured parameters in Nyagatare site, while Tonga presented less variability among the measured parameters. The variables captured by PCA (principal component analysis) indicated a difference in responsiveness towards applied treatments. In Nyagatare site, soybean GY, GNUP, GPUP, GKUP, and SPUK, contribute strongly to the variability of the system, and considerable contribution was observed from SY, SKUP, OC, Ca^{2+}, pH, and Mg^{2+} in Dim1. However, soybean HI and available P showed negative correlations with the other measured variables and were not correlated each other. Although they contributed to the overall variability of the system, this suggests that their variation may be influenced by external factors other than vermicompost, nitrogen and phosphorus fertilizer rates. In Tonga, HI, TN, and AP presented a strong relationship among themselves. For the maize crop, the first two principal components explained 65.9% and 12.4% of the total variance (Fig 3). In Nyagatare, GNUP, GKUP, GY, exchangeable Ca^{2+}, exchangeable Mg^{2+}, exchangeable K^{+}, OC, HI, and GPUP were positively correlated and greatly contributed to the maize grain yield (GY). This implies a greater conversion efficiency of the applied fertilizers into maize grain production. In Tonga site, maize SY, SKUP, SPUP, available P and TN largely contributed to the variability of the system in Dim1. Furthermore, these measured variables were positively correlated and more strongly associated with maize straw than with maize grain yield, indicating a relatively low efficiency of nutrient uptake and conversation into grain, but also greater utilization of nutrients such as K in leaves than grain. Soil Mg^{2+} and maize HI showed weak correlations at both the Nyagatare and Tonga sites.

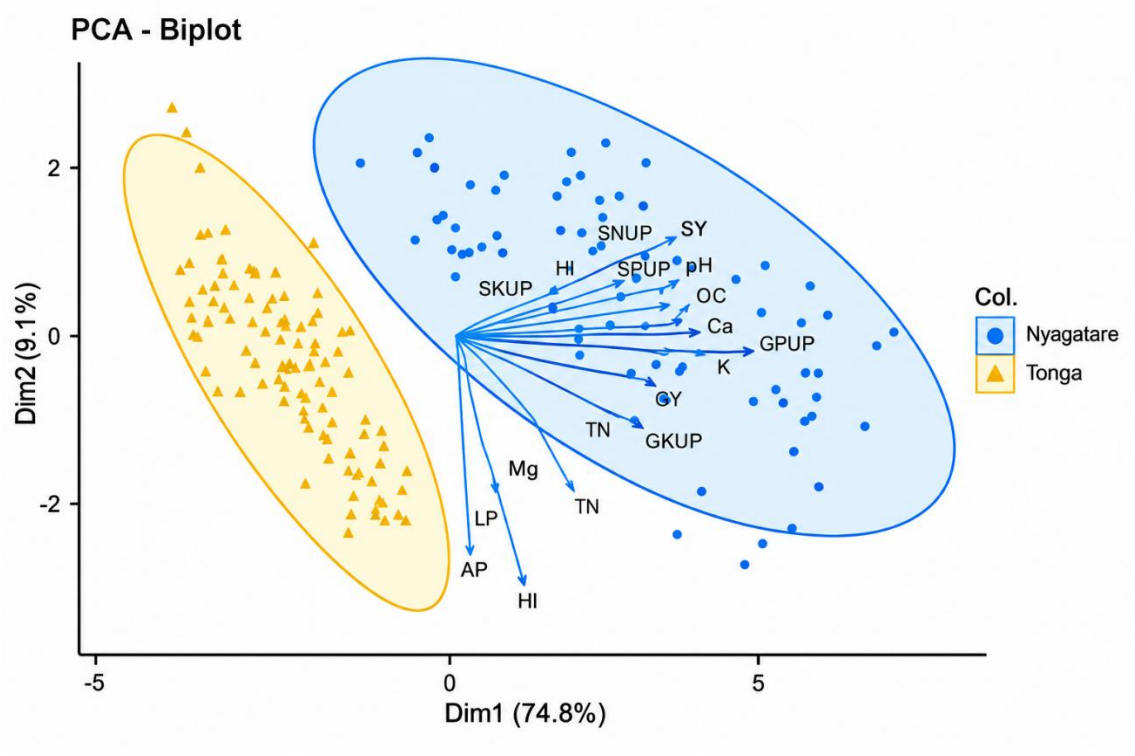


Fig 1. Principal component analysis (PCA) biplot presentation of correlation between multiple variables for soybean at Nyagatare and Tonga sites, Rwanda; GY: grain yield, SY: straw yield, HI: harvest index, OC: organic carbon, pH: hydrogen potential, TN: total nitrogen, AP: available phosphorus, K: potassium (K^+), Ca: calcium (Ca^{2+}), Mg: magnesium ($Mg2^+$), GNUP: nitrogen uptake in grain, GPUP: phosphorus uptake in grain, GKUP: Potassium uptake grain, SNUP: nitrogen uptake in straw, SPUP: phosphorus uptake in straw and SKUP: potassium uptake in straw

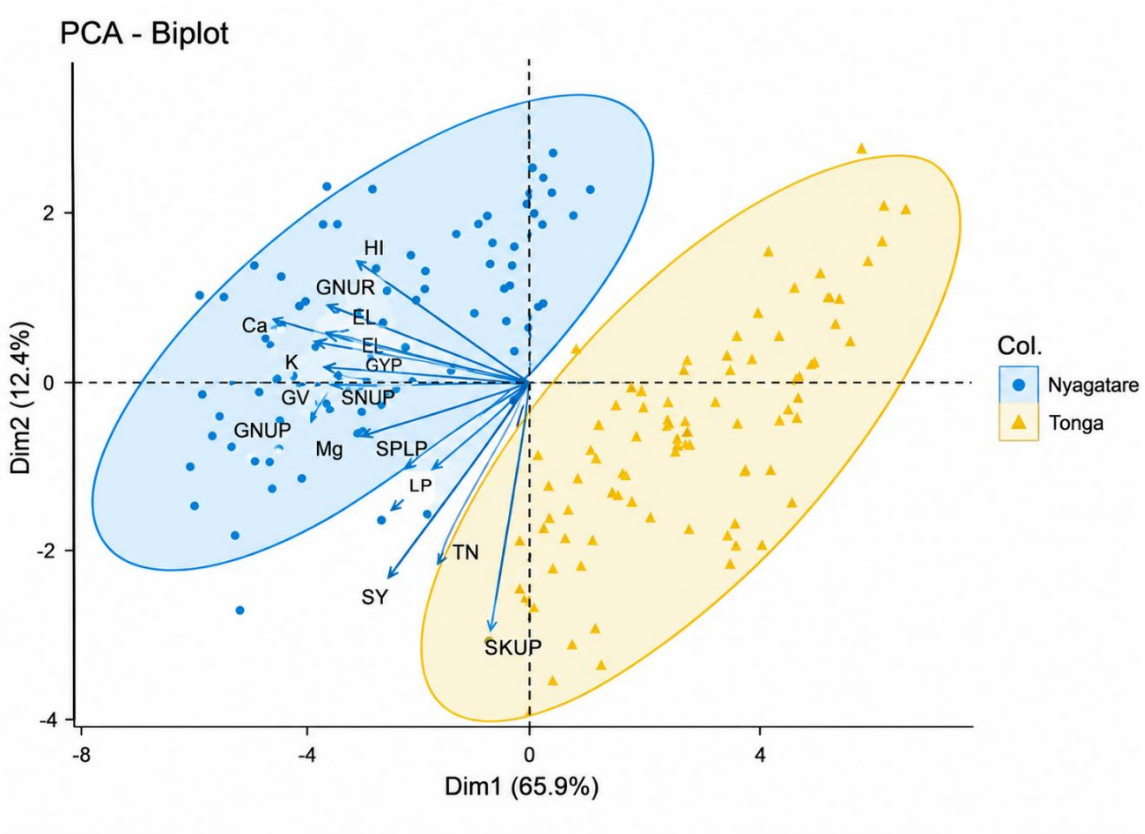


Fig 2. Principal component analysis (PCA) biplot presentation of correlation between multiple variables for maize at Nyagatare and Tonga sites, Rwanda; GY: grain yield, SY: straw yield, HI: harvest index, OC: organic carbon, pH: hydrogen potential, TN: total nitrogen, AP: available phosphorus, K: potassium (K^+), Ca: calcium (Ca^{2+}), Mg: magnesium ($Mg2^+$), GNUP: nitrogen uptake in grain, GPUP: phosphorus uptake in grain, GKUP: Potassium uptake grain, SNUP: nitrogen uptake in straw, SPUP: phosphorus uptake in straw and SKUP: potassium uptake in straw

3.8 Correlation matrix analysis

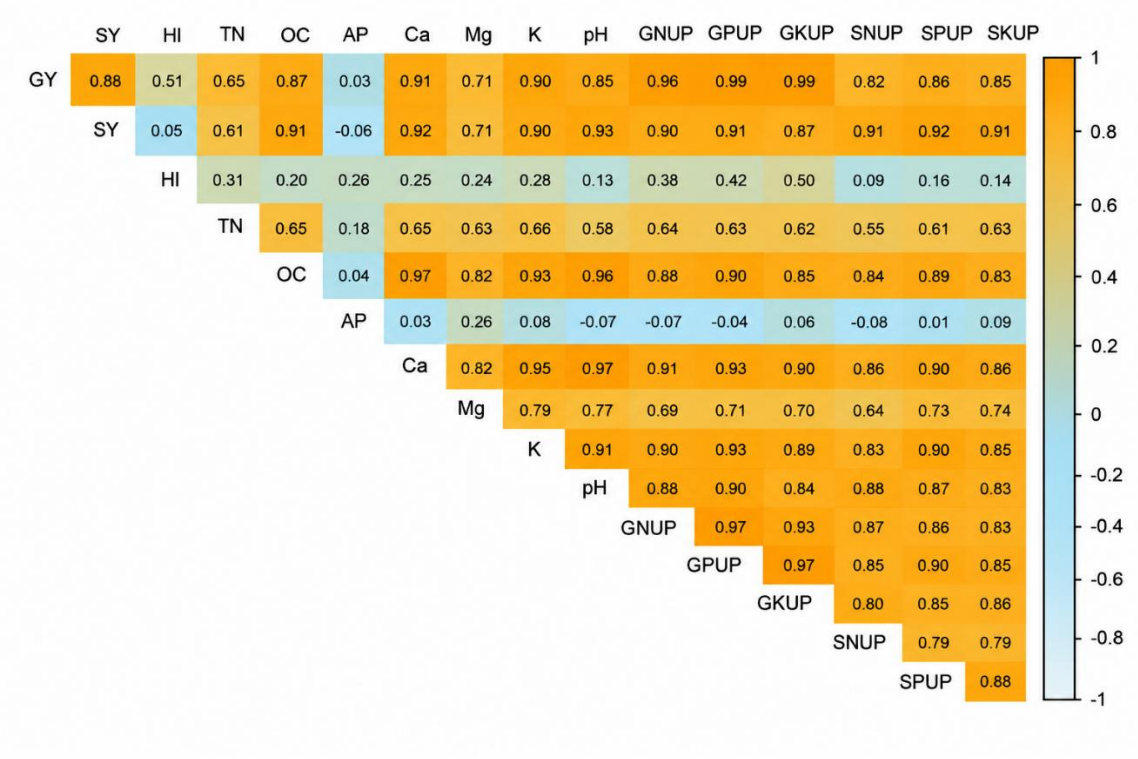
The correlation analysis results indicated that soybean grain yield (GY) was strongly and positively associated with straw yield (SY), soil total nitrogen (TN), organic carbon (OC), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), soil pH, nitrogen uptake in

grain (GNUP), phosphorus uptake in grain (GPUP), potassium uptake in grain (GKUP), nitrogen uptake in straw (SNUP), phosphorus uptake in straw (SPUP) and potassium uptake in straw (SKUP) (Fig 3). A similar trend was observed between straw yield and soil properties, crop nutrient uptake variables, indicating a closely linked relationship between biomass production and nutrient dynamics. Conversely, harvest index presented poor to moderate correlation with other variables, while the available phosphorus showed poor to negative association with other variables. In contrast, available phosphorus (AP) exhibited weak correlation with exchangeable bases and plant nutrient uptake. This weak association may be attributed to the fact that phosphorus availability is primarily governed by biological processes, including microbial mineralization and root exudation, as well as strong sorption and precipitation reactions, rather than cation exchange mechanisms. Consequently, phosphorus dynamics are often decoupled from exchangeable base cations in the soil system. Furthermore, a strong positive link was observed among exchangeable bases (Ca2+, Mg2+, K+), soil pH, and both grain and straw nutrient uptake, suggesting a synergetic effect of soil chemical properties in regulating nutrient availability and plant uptake processes.

As illustrated in Fig 4, the correlation analysis revealed that maize grain yield was strongly and positively correlated with harvest index (HI), soil organic carbon, exchangeable calcium (Ca^{2+}), potassium (K^{+}), pH, nitrogen uptake in grain (GNUP), phosphorus uptake in grain (GPUP), potassium uptake in grain (GKUP), and nitrogen uptake in straw (SNUP). In contrast, straw yield exhibited a weak association with soil TN, straw phosphorus uptake (SPUP), and a negative correlation with straw potassium uptake (SKUP). Soil TN was poorly to moderately correlated with other soil properties and crop nutrient uptake. Soil organic carbon was strongly and positively correlated with soil exchangeable base cations as well as grain nutrient uptake variables. Soil available P (A) was moderately correlated with soil chemical properties and nutrient uptake. A strong positive correlation was observed for exchangeable calcium (Ca^{2+}), potassium (K^{+}), and soil pH, which were also strongly positively related to maize grain nutrient

742 uptake variables, but with weak correlation with straw phosphorus and potassium
743 uptake.

744



745

746 **Fig 3. Correlation matrix between soybean yield, soil properties and nutrient**
747 **uptake** (Note: GY: grain yield, SY: straw yield, HI: harvest index, OC: organic carbon, pH:
748 hydrogen potential, TN: total nitrogen, AP: available phosphorus, K: potassium (K^{+}), Ca:
749 calcium (ca^{2+}), Mg: magnesium ($Mg2^{+}$), GNUP: nitrogen uptake in grain, GPUP: phosphorus
750 uptake in grain, GKUP: Potassium uptake grain, SNUP: nitrogen uptake in straw, SPUP:
751 phosphorus uptake in straw and SKUP: potassium uptake in straw

752

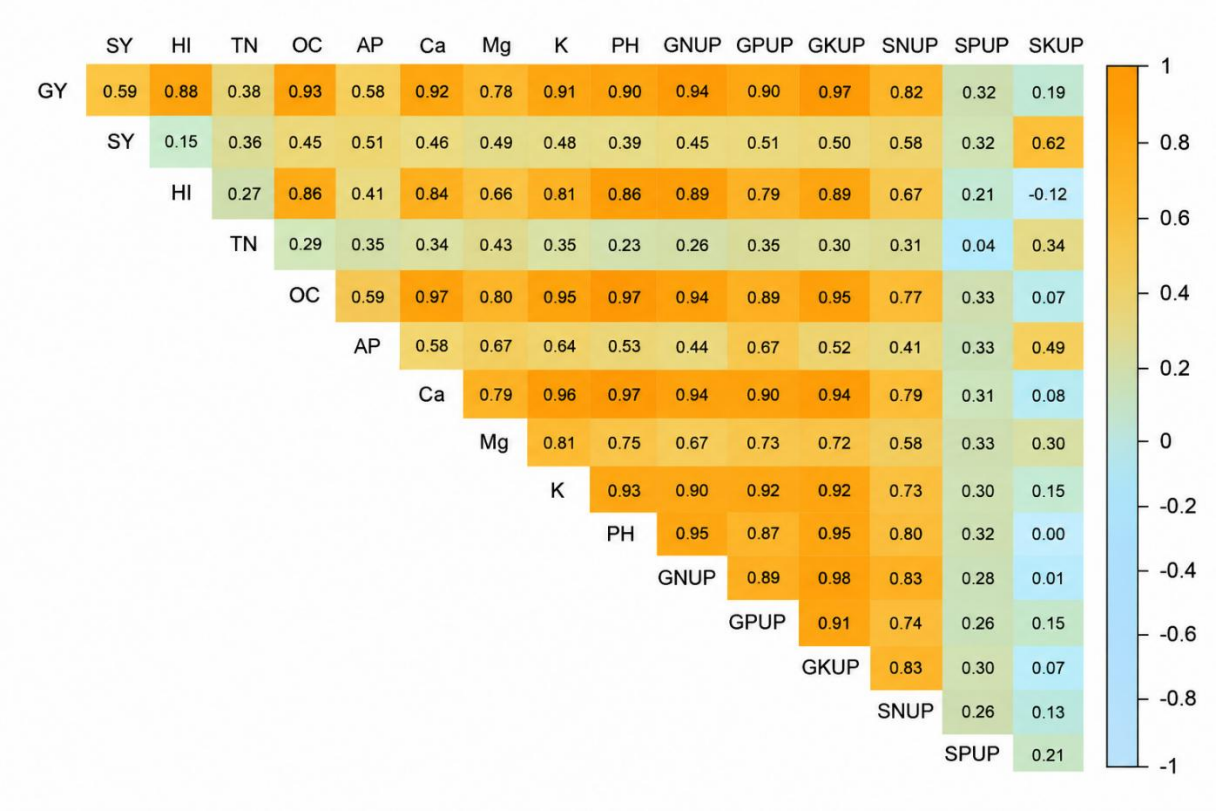


Fig 4. Correlation matrix between maize yield, soil properties and nutrient uptake

(Note: GY: grain yield, SY: straw yield, HI: harvest index, OC: organic carbon, pH: hydrogen potential, TN: total nitrogen, AP: available phosphorus, K: potassium (K^+), Ca: calcium (ca^{2+}), Mg: magnesium ($Mg2^+$), GNUP: nitrogen uptake in grain, GPUP: phosphorus uptake in grain, GKUP: Potassium uptake grain, SNUP: nitrogen uptake in straw, SPUP: phosphorus uptake in straw and SKUP: potassium uptake in straw

4. Discussion

The results indicated that soil chemical properties, yield and nutrient uptake were significantly influenced by the application of vermicompost, nitrogen and phosphorus fertilizer rates. Higher soil improvement, greater yield and nutrient uptake were attributed to the positive influence of the applied vermicompost and inorganic fertilizers at both sites than no fertilizers treatment. Given the increasing demand for improved soil and crop productivity, understanding how vermicompost and inorganic nitrogen and phosphorus fertilizers modify soil properties such as soil OC, pH and nutrients is essential.

Soil fertility amendment influenced the measured soil chemical properties in all seasons and across the sites. Relatively higher Soil TN, OC, Available P, Ca^{2+}, Mg^{2+}, and K^{+} and TN, Available P were observed in the plots treated with high rates of vermicompost (V), nitrogen (N), and phosphorus (P) fertilizer rates and their interaction in the first season of the year 2022. The combined use of vermicompost, nitrogen and phosphorus fertilizers enhance soil chemical properties due to the humified organic matter in vermicompost, which contributes to building soil organic carbon and improving soil's nutrient retention capacity. Furthermore, considerable improvement in soil chemical properties observed was due to application of vermicompost fertilizer and its interaction with nitrogen and phosphorus fertilizer rates.

An increase of 33.2% OC, 54.8% K^{+} and soil pH of 8.7% in Nyagatare and 54.8% OC, 37.6% $Ca^{2+,}$ 40.1% Mg^{2+}, 38.2% K^{+}, 70.7% available P, and soil pH of 6.8% in Tonga was obtained from the plots treated with the combination of the maximum rates of vermicompost and inorganic fertilizers. Consequently, the interaction of vermicompost and inorganic fertilizers resulted in superior soil property improvement compared to the non-fertilized control. This may be attributed to the enhancement of mineralization of N and P and secondary nutrients (as well as exchangeable Ca^{2+}, exchangeable Mg^{2+}, and exchangeable K^{+}) from vermicompost integrated with the inorganic sources of fertilizers, and improved soil chemical nutrient content and soil organic matter, as stated by Gebrekidan et al.[37]. Soil pH increased with an increase in vermicompost rates.

The observed increase was likely due to the organic matter in vermicompost, which contributes to improving soil pH, particularly in acidic soils. Lelei et al. [29]reported the positive effect of organic and chemical fertilizers on soil chemical properties under maize plantation in Tanzania.

A substantial increase in soybean yield was observed with the application of vermicompost relative to chemical fertilizers. However, the interaction of vermicompost, nitrogen and phosphorus fertilizer rates contributed to a positive increase in soybean harvest index, grain yield (GY), straw yield (SY), and harvest index (HI) due to the synergetic effect of those fertilizers. Soybean GY, SY, and HI increased by 32.9%, 44.6% and 59.2% in Nyagatare and 54.6%, 25.9% and 42.3% with an increase in the level of vermicompost, nitrogen, and phosphorus. These increases might be due to the contribution of phosphorus fertilizer to plant root growth and development and transfers energy to the different parts of the plant, adequate availability of soil moisture and better spread of the roots of the crop into the soil and timely uptake of soil nutrients, and reduced leaching of nutrients in the soil due to the increase of soil organic matter. These findings consisted with the recent study by Manore [41] who reported an increment in mung bean yield due to the application of vermicompost and chemical fertilizer rates. Moreover, the application of vermicompost along with nitrogen fertilizer increased the soybean yield, probably due to the adequate supply of macro and micronutrients, chlorophyll production, and photosynthesis, which in turn gives carbohydrates as they accumulate assimilates to the soybean, hence more yield [31]. Furthermore, the nitrogen application may mitigate the diverse effects of water stress by enhancing physiological processes and crop resilience under rainfed conditions, as reported by Waraich et al. [42]. The uptake of nitrogen, phosphorus, and potassium in both soybean grain (GNUP, GPUP, and GKUP) and straw (SNUP, SPUP, and SKUP) increased with the application of high rates of vermicompost and inorganic fertilizers, compared to plots without amendments. The enhanced nutrient uptake corresponds to an increase in soybean grain and straw yield in both sites, which can be attributed to improved soil chemical properties. The organic matter in vermicompost improved soil organic carbon, which facilitated the release of essential nutrients, thereby supporting

plant growth and greater nutrient accumulation in soybean grain. The observed rise in nitrogen uptake with increased N fertilizer application was likely due to starter N applied, which was well synchronized with the development and growth of soybean, hence enough photosynthetic rate and N accumulation in soybean grain, finally leading to a good yield. This result is in accordance with findings reported by Xu et al. [45], who stated that higher rates of nitrogen fertilization rates stimulated the activities of key enzymes involved in nitrogen metabolism within plant roots, thereby enhancing nitrogen absorption and translocation to shoots, which leads to increasing both soybean yield and nitrogen uptake.

Moreover, the observed rise in nitrogen uptake with increased N fertilizer is associated with enhancement of nutrient absorption through symbiotic associations with plant roots and expanded hyphal structure into the surrounding soil, thereby enhancing the movement and availability of nitrogen, transfer of nitrogen compounds like ammonium (NH_4^+) and nitrate (NO_3^-) to the plant root zone [36]. Furthermore, this symbiotic relationship also mobilizes phosphorus into the soil and enhances its uptake by the crop. Moreover, the combined application of nitrogen and phosphorus fertilizer rates significantly boosted the uptake of P and K in soybean grain, as well as potassium uptake in straw, particularly in Nyagatare. The increase in nutrient uptake may be attributed to the supply of readily available nutrients supplied by mineral fertilizers, which leads to better growth and yield [37]. Moreover, in Tonga, an increase in nitrogen and phosphorus uptake in soybean grain was observed with higher rates of vermicompost combined with nitrogen and phosphorus fertilizers, suggesting a synergistic enhancement of nutrient availability and plant uptake. This response is likely driven by the immediate supply of readily available N and P from inorganic fertilizers, together with the gradual release of mineralized N and P during vermicompost decomposition, resulting in greater nutrient availability to the plant compared to non-fertilized treatments. In addition, the increase of phosphorus uptake by soybean grain may be attributed to the increased P solubilization driven by organic acids released during microbial decomposition of vermicompost, which convert sparingly soluble phosphorus forms into available fractions to plant [38]. Consequently, combined vermicompost and inorganic fertilizers application enables plants to achieve greater

assimilation of the nutrients required, which are then translocated into the soybean grain [39]. This process boosts both dry matter content and soil nutrient content, ultimately resulting in higher nutrient uptake by soybean grain. This aligns with the results of Mamun et al.[40], who claimed improved soybean phosphorus uptake in the field experiment, whereby vermicompost was combined with inorganic fertilizers.

The observed increase in maize grain yield (GY) at both sites was attributed to the combined application of vermicompost (V) with nitrogen (N) and phosphorus (P) fertilizers. Given maize ‘s high nutritional demand, particularly for nitrogen, the enhanced yield likely resulted from the increased nutrient supply provided by higher rates of vermicompost, nitrogen, and phosphorus. This improved nutrient availability and facilitated greater nutrient uptake, resulting in high grain yields. Additionally, vermicompost enriches the soil with humic substances, such as humic acids, which enhance biological activity and nutrient use efficiency, thus further contributing to increased maize productivity [32]. Maize crop has a high nutrient demand, especially nitrogen. The superior performance of the interaction effects of vermicompost and nitrogen in enhancing maize grain yield and grain potassium uptake can be attributed to improved and sustained soil nutrient availability per se macro and micronutrients; hence promotes efficient nutrient assimilation into plant biomass and grain yield [33,34]. Furthermore, the interaction between vermicompost and nitrogen fertilizer rates exhibited effects on maize grain yield comparable to those observed for the combined application of nitrogen and phosphorus fertilizer rates. This interaction also enhanced nitrogen and potassium uptake in maize grain, as well as nitrogen uptake in straw. These responses are likely due to the rapid availability of nutrients supplied by mineral fertilizers, which promotes vigorous vegetative growth, greater dry matter accumulation, and improved yield formation. These findings were consistent with previous studies, for instance Srinivasan et al. [53] reported superior performance of recommended NPK fertilizer application compared to sole organic amendments in the cabbage-baby corn cropping system. Similarly, Omirou et al. [39] demonstrated that application of ammonium nitrate (NH_4NO_3) significantly increased barley grain and straw yields, showing trends comparable to those obtained with organic fertilizer inputs. Moreover,

the observed increase in maize straw phosphorus uptake due to co-application of vermicompost, nitrogen and phosphorus fertilizers can be explained by their complementary roles. Nitrogen fertilizer supplies readily available nutrients, while vermicompost enhances soil organic matter, stimulates microbial activity, and improves nutrient retention capacity. Phosphorus fertilizer, in turn, promotes root development, facilitating more efficient nutrient acquisition and sustained release throughout the growing season. This synergistic effect reduces nutrient losses through leaching and enhances nitrogen availability, uptake, and translocation into maize biomass compare with unfertilized treatments [43–45].

During the field experiment, all fertilizers applied had a positive correlation with soybean and maize yield. Further, fertilizer types and rates also showed a positive correlation with soil chemical properties and nutrient uptake, and the variables had a positive correlation between themselves. Soybean and maize grain yield, straw yield, and harvest index were positively correlated, and influenced by the fertilizer types and rates and results into high yield. Moreover, these findings are consistent with the previous studies demonstrating that the soil organic carbon plays a central role in enhancing crop productivity by improving nutrient availability, soil structure, and microbial activity [34,35]. In addition, exchangeable calcium contributes significantly to soil aggregation, structural stability, and nutrient retention, which lead to crop productivity [36]. The strong positive correlations observed between soil organic carbon and exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}),, as well as nutrient uptake, further indicate that organic matter enhances cation exchange capacity and nutrient retention, ultimately increasing nutrient supply to crops [37].

4.1. Limitations of the study and future work directions

This study was conducted at a low altitude in Nyagatare and mid altitude in Tonga zones of Rwanda to assess the performance of short rotation soybean-maize cropping systems. However, the field experiment covered only one cropping season for each crop, limiting the assessment of the consistency and reproducibility of crop responses to the application of vermicompost, nitrogen, and phosphorus fertilizer rates across

seasons. The research timeline, together with the financial constraints, restricted the opportunity to repeat the experiment over multiple growing seasons. Therefore, the findings should be interpreted within the specific agroecological and seasonal conditions under which the field experiment was carried out, and their generalization across seasons and other production environments remains to be established. Consequently, future research should focus on multi-season experiments over a wide range of agroecological zones to quantify season variability and ensure the consistency of the crop responses due to the application of vermicompost and mineral fertilizers. Further research should also emphasize the long-term agronomic performance of soybean-maize rotations to support the development of sustainable cropping systems under smallholder farmers in Rwanda.

5. Conclusion

Soybean and maize are among the most important crops grown in Rwanda, commonly grown under rotational systems and widely utilized in food and feed processing industries. However, their productivity remains constrained by declining soil fertility and the limited application of organic amendments, which negatively affect soil fertility, crop yield and nutrient uptake. The present study demonstrates that the integration of vermicompost with nitrogen and phosphorus fertilizer rates significantly improves key soil properties, including soil OC, soil pH, and exchangeable base cations ($Ca^{2+,}$ Mg^{2+}, and K^{+}). These improvements are attributed to enhanced organic matter content, an increase in nutrient retention, and gradual nutrient release. Consequently, a substantial increase in soybean harvest index and maize yield, as well as crop nutrient uptake. Notably, the experimental results clearly indicate that combining the high rates of vermicompost with chemical fertilizers (7 t V7 t V: 27 kg N: 69 kg P_2O_5 ha^{-1} and 7 t V: 96 kg N: 69 kg P_2O_5 ha^{-1}) improves soil fertility, crop productivity and nutrient acquisition in soybean-maize short rotation systems. These findings underscore the effectiveness of integrated nutrient management strategies in enhancing both soil quality and crop performance.

Multivariate analyses, including principal component analysis and correlation assessment, further revealed strong positive associations between crop yield, nutrient uptake, and soil fertility indicators, particularly soil OC and exchangeable base cations; that are identified as the key drivers of nutrient availability and crop productivity. In addition, site-specific variations were evident; Site-specific differences were evident, Nyagatare site exhibited greater variability and strong relationship with co, greater variability and stronger associations with crop yield were observed, while Tonga exhibited greater variability and stronger relationships with crop yield, whereas Tonga site showed relatively stronger associations with straw biomass, suggesting differences in nutrient use efficiency and biomass partitioning across agroecological conditions. From a practical perspective, integrating vermicompost, nitrogen and phosphorus fertilizer rates should be promoted among smallholder farmers as a sustainable approach to improving soil health and maintaining agroecosystem productivity. Agricultural extension services and supportive policy frameworks are recommended to scale up this practical approach, particularly in similar agroecological zones. Future research should focus on evaluating the long-term agronomic and economic impact of these integrated approaches across diverse farming systems.

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