

RESEARCH ARTICLE

# Residual effect of vermicompost and preceding groundnut on soil fertility and associated *Striga* density under sorghum cropping in Eastern Ethiopia

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## Abstract

Depletion of soil organic matter was found to be the primary biophysical factor causing declining per capita food production in sub-Saharan Africa. The magnitude of this problem was exacerbated by moisture-stress and imbalanced fertilizer application that caused *Striga* weed infestation. To address such confounded issues, two-year field experiments were conducted to evaluate the effect of residual vermicompost and preceding groundnut on soil fertility, sorghum yield, and *Striga* density. The first-year treatments contained two sowing methods (single and intercropped sorghum), two seedbed types (open-furrow and tied-ridge), and four vermicompost rates (0, 1.5, 3.0, and 4.5 t/ha) combined factorially in a randomized block design. In the second-year experiment, only monocropped sorghum with seedbed types was sown exactly on the same plot as the previous year's treatment combinations without fertilizer. The results disclosed that residual vermicompost at 4.5 t/ha in intercropped sorghum/groundnut significantly reduced soil pH (0.76%), bulk density (8.61%), electrical conductivity (38.78%), and *Striga* density (85.71%). In contrast, compared to unamended soil, the aforementioned treatment combined with tied-ridging increased soil moisture, organic matter, and sorghum yield by 16.67, 2.34, and 58%, respectively. Moreover, this treatment combination markedly increased post-harvest soil organic carbon (7.69%), total N (0.247%), available P (38.46%), exchangeable-Fe (27%), and exchangeable-Zn (40%) in the second year over control. Treatments previously amended with 4.5 t/ha of vermicompost under the sorghum-groundnut intercrop system resulted in the highest total N (0.242%) and available P (9.822 mg/Kg). Thus, the vermicompost and groundnut successfully improve soil fertility and sorghum yield for two cropping seasons.

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## Introduction

Poor soil fertility is one of the greatest biophysical constraints adversely affecting the food security of millions in sub-Saharan Africa (SSA) [1,2]. These problems were highly exacerbated

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by unbalanced fertilizer application [3,4], severe depletion of soil organic matter (SOM) [5,6], and overuse of crop residues for home consumption instead of as fertilizer [2,7,8]. According to Beshir & Abdulkarim [9], the situation was predominantly noticeable in Ethiopian dryland regions, which exacerbated the spread and tenacity of the *Striga hermonthica* (Del.) Benth weed infestation in SSA [10,11]. This disastrous weed regulates the flow of water and nutrients from the host to itself using an organ known as haustoria [10,12,13]. Numerous studies suggested that the combination of improved soil fertility with *Striga*-resistant varieties was one of the sustainable ways to overcome the menace of *Striga* weed [14–17]. Similarly, to stifle this parasitic weed, there was a high possibility of replacing escalating chemical fertilizer prices with low-cost and high-quality organic matter [1,18,19]. High-quality organic matter could be used for soil bioremediation via modifying soil rhizosphere, promoting microbial diversity, and enriching soil enzymes [20,21]. This enhances host-plant resistance and/or tolerance in post-attachment stages [17,22]. SOM is also used as the reservoir of essential plant nutrients [23,24] that had a high residual (carryover) effect for the following crops [25] and may last for many years [26].

In this scenario, the application of vermicompost was suggested as the most promising and eco-friendly natural fertilizer [21,27,28] that could mitigate soil degradation and replenish SOM [23,29]. The most described features that make vermicompost an effective fertilizer is its high homogeneity, porosity, water-holding capacity, readily available plant nutrients, and low C:N ratio [30–32]. Providing an optimal nutrient level, could correct “Liebig’s Law of the Minimum” and mitigate the high cost of chemical fertilizer [20,21], resulting in high agronomic, economic, and environmental benefits [33]. Following the Law of the Minimum, vermicompost is beneficial not only for crop nutrition but also for reducing plant constraints on other resources like water, disease, plant growth hormone, etc. [32]. This vermicompost would be easily prepared at low cost [34] from locally affordable raw materials such as *Catha edulis* Forsk [35], *Parthenium hysterophorus* L. [36,37], *Lantana camara* L. [38,39], *Prosopis juliflora*, etc. [40]. Furthermore, the use of vermicompost has multifold benefits, such as tackling the competing issue (frequent removal) of farmyard manure (FYM) and crop residue [7,8]. It also creates new job opportunities for rural households, particularly for women [38–42]. *P. hysterophorus* [40] and *L. camara* [38] are the most invasive and problematic weeds in terrestrial ecosystems that have greatly disturbed human welfare.

Currently, the distribution of these notorious weeds is spreading rapidly and extensively [43,44] thereby results in 97–100% yield reductions of field crops in eastern and southern Africa [45]. Management of these weeds through mechanical, biological, and chemical means was too difficult and ineffective [39,43,46]. Direct incorporation of their green matter (residues) also poses detrimental effects on crops and soil health due to its toxicity [47]. Additionally, these low-quality organic materials immobilized soil nutrients, prolonging the soil infertility cycle [2]. Thus, management of these notorious weeds through utilization, particularly by vermicomposting, is the only sustainable way to destroy their allelopathic (*phenolics* and *sesquiterpene lactones*) and toxic properties [37,40,47,48].

Nevertheless, the decomposition and nutrient-releasing rate of applied vermicompost in dryland agriculture were predominantly influenced by soil moisture stress [20,49] that negatively affected microbial growth and nutrient diffusion [50,51]. In this regard, employing tied-ridge tillage [20,50–53] with a cereal-legume intercropping system would effectively conserve soil moisture and assist rate of decomposition and nutrient release [9,54,55]. According to Cong *et al.* [56], intercropping hastens SOM decomposition, probably associated with a lower soil C:N ratio, higher litter input, a change in the rhizosphere system, and better N retention. Besides this, incorporating legumes in cereal crops delivers additional income, nutritional benefits, and N to the soil system [1], while reducing *Striga* weed pressure [3]. Intercropping systems strongly influenced soil microbial diversity, structure, and function [57,58], besides

improving plant growth traits [59], which was conducive to improving soil nutrient-supplying capacity and microecosystem stability [60,61].

Furthermore, intercropping exhibited high ground-cover due to more shading compared to sole cropping, thus lowering soil evaporation and increasing the SMC [62]. Studies have also shown that legume crops have substantially residual benefits for cereals [63]. The authors further found that the total amount of nitrogen carried over from diverse legumes to successive crops in soybean, peanut, and chickpea ranged between 54 and 68 Kg per ha. On the other hand, a tied-ridge substantially improves soil water by decreasing surface water flow velocity and bulk density [64]. These practices aid in reducing the spread of *Striga* weed to other fields [14,65,66]. However, the integrated use of vermicompost and tied-ridging under a sorghum-intercropping system was poorly understood despite being of valuable importance in protecting plants from *Striga* weed invasion and water stress. As per Ekeleme *et al.* [67] and Yang *et al.* [68], the majority of the evidence that is currently available about the impact of vermicompost on soil physico-chemical parameters was obtained in a controlled environment. Apart from this, there was meager information on the effects of the preceding groundnut and leftover vermicompost on *Striga* density. Liu *et al.* [69] also noted the effect of preceding legumes on subsequent crop yield, and soil has not been well explored.

Determining the target nutrient needed for a subsequent crop begins with understanding the soil's fertility status and the residual effects of applied fertilizer. The effective application of this technology therefore needed a deeper comprehension of such synergistic impacts on soil physico-chemical characteristics. Moreover, Erkossa *et al.* [4] state that more comprehensive efforts were required to raise knowledge in order to distract farmers from the usage of synthetic fertilizer, which was previously supported by Ethiopian government subsidies. Hence, we hypothesize that the residual effect of vermicompost combined with a tied-ridge under the sorghum/groundnut intercropping system would resolve the most yield-limiting factors such as soil infertility, moisture stress, SOM depletion [5,6], and severe *Striga* infestation [10,11]. Thus, we intended to evaluate the residual effects of vermicompost and preceding groundnut intercropped with sorghum under various seedbed types on soil physio-chemical properties, *Striga* density, and sorghum yield. Subsequently, we aimed to control the most destructive invasive weeds via the vermicomposting process.

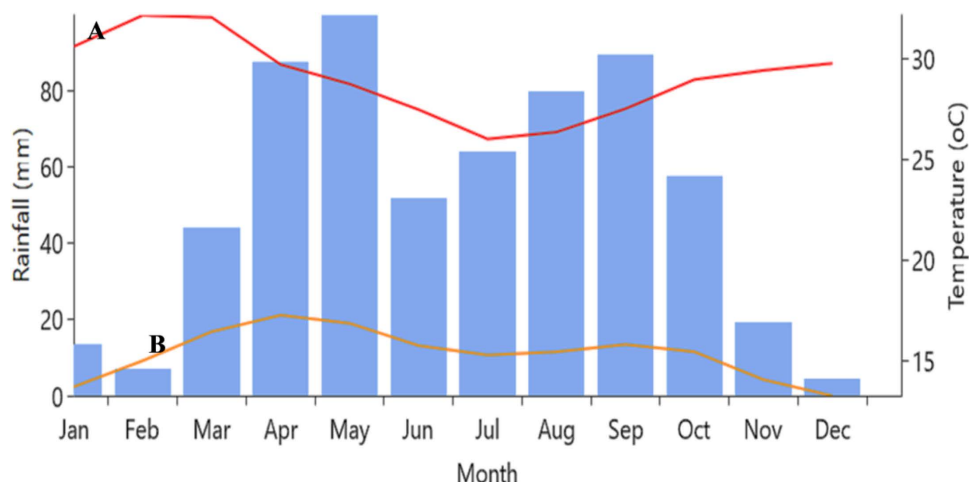
## Materials and methods

### Site description

The experiment was conducted in a farmers' field at Kile-Besidimo Plain in the 2021 and 2022 years. Kile-Besidimo is one of the smallest farmers administrative associations in the Sofi district of Harari Region in eastern Ethiopia. This research was approved by Haramaya University (HrU) Post Graduate Director and Office of Research Affairs, with special responsibility given to the "PES Research Thematic Area Leaders," for directing field site and project-related activities. The geographical location of the site is 42° 27' N latitude and 9° 12' E longitudes and an altitude of 1400 meters above sea level. The district has a bimodal rainfall distribution pattern with heavy rains in April and May, while the long and erratic rainy month stretches from June to October (Fig 1). The average annual rainfall amount is 249.2 mm, and the maximum and minimum temperatures are 21.9°C and 10.6°C, respectively (Fig 1). The site was known for its monoculture cropping history, particularly sorghum.

### Vermicompost preparation

The fresh biomass of *L. camara*, *P. hystrophorus*, and animal dung as well as dried wheat straw was collected from HrU and its vicinity areas. After the plant residues were chopped



**Fig 1. Long-term (1991–2022) monthly rainfall (bar), maximum (A), and minimum (B) temperature at Kile site.**

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into small pieces (2–3 cm), each substrate was weighed in an equal amount (3 Kg) and mixed all together, then fresh animal dung was added in a 1:2 ratio of dry plant residue on a weight basis. The mixture was moistened and turned manually every day for three weeks as pre-composting (partial fermentation) in a previously constructed vermiculture house at the HrU Raree Research Site. This vermiculture station comprises rooms for worm rearing, substrate preparation, and vermicomposting, as well as drying and storage with sufficient shade and ventilation. This process made feeds more biodegradable and palatable to worms [21]. Young *Eisenia fetida* were added to mixed substrate filled in a worm bin according to the recommendation in proportion by Shirani *et al.* [30], in which 25 g of earthworms were added per 1 Kg of cow manure. Beside their fecundity and suitability, *Eisenia fetida*, so-called eco-biological engineer [70], consumes organic matter equal to their body weight every day [71]. The mixture was maintained moist by spraying water every five days to regulate the worm bins optimum range of temperature (15–25°C), moisture (65–75%), and pH (6.5–7.2). The matured vermicompost was harvested, air dried, and added to determine its chemical properties, ready for use as fertilizer.

## Treatments and experimental procedures

Field experiments were conducted for two consecutive years, 2021 and 2022, using two crop cultivars: ‘Melkam (WSV387)’ for sorghum [*Sorghum Bicolor* (L.) Moench] as a base crop and ‘Babile-1 (ICGV-98412)’ for groundnut [*Arachis hypogaea* L.] as a component crop. The first-year trial consisted of sole and intercropped sorghum with groundnut combined with/without (i) two seedbed types (open-furrow and tied-ridge) and (ii) four vermicompost rates (0, 1.5, 3.0, and 4.5 t/ha), which were factorially arranged using a randomized complete block design with three replications (Table 1). These vermicompost rates were calculated based on previously recommended fertilizer in the sole crop method for sorghum [72] and groundnut [73] in the study area. We also take into consideration the negative effect of excess vermicompost on salinity and  $N_2$ -fixation suggested by Oyege & Bhaskar [21].

Tied-ridge is a type of *in-situ* soil moisture conservation tillage in which a ridge of 20 cm high with 3–5 cm thickness was created with a ridge maker fitted on a tractor and was tied at 1.5-m intervals manually [74]. The crossties are kept lower than the ridges, so they act as spillways in the event of heavy rainfall to reduce soil erosion. These micro-basin tillage types

Table 1. Treatment combinations in the first-year and second-year cropping systems for sorghum.

First (2021) year Treatments				Second (2022) year Treatments			
No	Combinations	No	Combinations	No	Combinations	No	Combinations
1	SSFV <sub>0</sub>	13	SB <sub>1</sub> FV <sub>0</sub>	1	SSF <sub>0</sub>	13	SS <sub>1</sub> F <sub>0</sub>
2	SSFV <sub>1</sub>	14	SB <sub>1</sub> FV <sub>1</sub>	2	SSF <sub>1</sub>	14	SS <sub>1</sub> F <sub>1</sub>
3	SSFV <sub>2</sub>	15	SB <sub>1</sub> FV <sub>2</sub>	3	SSF <sub>2</sub>	15	SS <sub>1</sub> F <sub>2</sub>
4	SSFV <sub>3</sub>	16	SB <sub>1</sub> FV <sub>3</sub>	4	SSF <sub>3</sub>	16	SS <sub>1</sub> F <sub>3</sub>
5	SSTdV <sub>0</sub>	17	SB <sub>1</sub> T <sub>d</sub> V <sub>0</sub>	5	SSTd <sub>0</sub>	17	SS <sub>1</sub> T <sub>d0</sub>
6	SSTdV <sub>1</sub>	18	SB <sub>1</sub> T <sub>d</sub> V <sub>1</sub>	6	SSTd <sub>1</sub>	18	SS <sub>1</sub> T <sub>d1</sub>
7	SSTdV <sub>2</sub>	19	SB <sub>1</sub> T <sub>d</sub> V <sub>2</sub>	7	SSTd <sub>2</sub>	19	SS <sub>1</sub> T <sub>d2</sub>
8	SSTdV <sub>3</sub>	20	SB <sub>1</sub> T <sub>d</sub> V <sub>3</sub>	8	SSTd <sub>3</sub>	20	SS <sub>1</sub> T <sub>d3</sub>

SS=sole sorghum; SB = intercropped sorghum with B<sub>1</sub> = *Babile-1* or B<sub>2</sub> = *Babile-2*; V = vermicompost; Td = tied-ridge; F = furrow-planting (conventional planting), SS<sub>1</sub> = sole cropped sorghum in previous *Babile-1*; F<sub>(0-4)</sub> = sorghum in furrow planting under previous applied rates of vermicompost; Td<sub>(0-4)</sub> = sorghum in tied-ridging under previous applied rates of vermicompost.

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increase surface retention capacity and nutrient availability via reducing runoff and nutrient losses from soil, thereby improving soil moisture content while reducing *Striga* dissemination to neighboring fields. Open-furrow is a shallow trench or row formed by conventional farmer practice (oxen-drawn traditional *maresha*), which is a bit deeper than a flatbed and shallower than a tied-ridge.

In the first main cropping season, the land was plowed and harrowed by a tractor to bring the soil to a fine tilth, and then sorghum and peanut were sown on 28 June 2021. In the second year, the land was carefully prepared using a spade without destroying and mixing the previous plot size as well as plot shape (Table 1). Under this year, only sorghum and seedbed types without fertilizer was sown on June 2, 2022, using the same plot and randomization of its first-year treatment combination. In all intercropping treatments, the row spacing between sorghum and groundnut was maintained at 37.5 cm with a net plot area of 3 m x 4 m (12 m<sup>2</sup>), with the space between each plot and the block remaining 1.0 m and 1.5 m, respectively. For the tied-ridge planting pattern, sorghum seeds were dribbled in the row of ridges, while groundnut seeds were planted on the ridges between the sorghum rows. Vermicompost was incorporated into the soil only in the first-year trial according to a predetermined rate to each plot a week before sowing. To keep the field weed-free except for *Striga*, manual weeding and hoeing operations were performed during both years of experimentation. All other necessary agronomic management practices were carried out uniformly as per standard recommendation for sorghum and groundnut cultivation.

## Sample collection

**Physico-chemical properties of soil and vermicompost.** For assessment of the fertility status of soils in the study area, a composite soil sample from a depth of 0–20 cm was taken at the beginning of the trial (2020) from the whole field as well as immediately after harvest of first-year (2021) and second-year (2022) crops from each plot. For better results, one composite sample was prepared for laboratory analysis from 4 sampling points per plot, avoiding the border effect. The physico-chemical properties of soil, as well as vermicompost that was free from earthworms and cocoons were analyzed at the HrU soil laboratory for specific parameters. Soil pH by potentiometric water extract (pH-H<sub>2</sub>O), electrical conductivity (EC mS/cm), total N (%) by the Kjeldahl method available P by the Olsen method cation exchange capacity (CEC), exchangeable bases (Ca, Mg, K, and Na)



by ammonium acetate, micronutrients (Zn, Fe, and Mn) by the *Ethylenediamine Tetra-acetic Acid* (EDTA) extraction method, and total organic carbon by the Walkley and Black method. Soil bulk density and moisture content were measured from undisturbed soil by the core method and gravimetric method, respectively. The weight of the wet soil was measured immediately after collecting the sample, while the dry weight of each sample was measured after oven drying at 105°C for 24 hours for both parameters. Moisture content was determined at the vegetative and early reproductive stages (during the 50% sorghum flowering stage) just after two days of rainfall. The following formula was used for calculating the soil moisture content (SMC).

$$SMC = \frac{W_w - W_d}{W_d} * 100$$

Where: SMC = soil moisture content dry base (%),  $W_w$  = weight of the wet soil (gm),  $W_d$  = weight of the dry soil (gm).

**Striga variable.** The number of emerging *Striga* plants in each plot was counted at intervals of two weeks [77, 91, 105, and 119 days after sowing (DAS)] from the four center rows of each net plot (3.4 m<sup>2</sup>) until all *Striga* matured to determine the maximum above-ground *Striga* number. *Striga* density was calculated following Nkoa *et al.* [75] and Travlos *et al.* [76] steps. It is one of the simplest and most common means of computing weed abundance [75].

$$\text{Striga density} = \frac{\text{Total Striga count per plot}}{\text{Harvested plot area (m}^2\text{)}}$$

Where: High *Striga* density indicates severe infestation.

**Sorghum parameters.** Stover yield and grain yield were measured after harvest from the net plot area (by discarding external rows). Following the adjustment of the moisture content to 12.5%, the grain yield of sorghum was measured and translated to tons per hectare (t/ha).

## Data analysis

Selected soil physico-chemical, *Striga* density, and sorghum yield data were subjected to analysis of variance (ANOVA) using R-Software (R-4.3.1 version). In all the comparisons, the level of significance was set at  $\alpha = 0.05$ . The hypotheses were tested at a 95% confidence interval, and the means were compared using the least significant difference (LSD) test.

## Results

### Quality of vermicompost and soil before planting

The result of laboratory analysis of vermicompost obtained from a mixture of all substrate materials had a neutral pH (7.1), high organic carbon (23.67%), an acceptable C:N ratio (12.24%), and medium EC (5.32 mS/cm) (Table 2). This compost also contains a higher percentage of essential plant nutrients than the initial soil analysis result (Table 2). At the beginning of the experiment, total N, available P, as well as exchangeable K, Mg, Ca, and organic matter in the top 30 cm soil layer were 0.01%, 3.48 mg Kg<sup>-1</sup>, 0.45 cmol (+)/Kg, 3.75 cmol (+)/Kg, 9.92 cmol (+)/Kg, and 1.08%, respectively. Correspondingly, initial soil results at the experimental site had a high bulk density (4.5 g cm<sup>-3</sup>), a medium CEC (18.17 cmol (+)/Kg), and low Zn and Fe contents.

Table 2. Preliminary physico-chemical properties of vermicompost and pre-treated soil.

Properties	Parameter values		Properties	Parameter values	
	VC	Soil		VC	Soil
pH (H <sub>2</sub> O)	7.25	7.1	Mn (mg/Kg)	19.467	1.3
EC (mS/cm)	5.32	3.33	Exch. Ca (cmol (++)/Kg)	32.77	9.92
Total N (%)	1.93	0.01	Exch. Mg (cmol (++)/Kg)	25.848	3.75
OM (%)	40.72	1.08	Exch. K (cmol (+)/Kg)	20.14	0.45
Av. P (mg/Kg)	20.14	3.48	CEC (cmol (+)/Kg)	43.5	18.17
Zn (mg/Kg)	44.42	0.19	Sand (%)	–	66.78
Fe (mg/Kg)	54.33	5.83	Clay (%)	–	15.06
BD (g/cm <sup>3</sup> )	–	1.45 (compact)	Silt (%)	–	18.16

VC = vermicompost; N = total nitrogen; OM = organic matter; Av.P = available phosphorus; Zn = zinc; Fe = iron; Mn = manganese; Exch = exchangeable cations (K = potassium, Mg = magnesium, and Ca = calcium); CEC = cation exchange capacity; EC = electrical conductivity; BD = soil bulk density.

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## Effect of residual vermicompost and groundnut on selected soil physico-chemical characteristics at Kile

**Soil organic carbon (SOC) and bulk density (BD).** The mean separation of the second-year post-harvest analyzed soil in Table 3 indicates that the single effects of the three factors, as well as their two-way interaction with vermicompost, significantly ( $P \leq 0.05$ ) affect soil BD (S2 Table in S1 File). However, only the main effects of the planting method and vermicompost, along with their two-way interaction, show significant differences for SOC (Table 3). The highest SOM matter (4.472%) was recorded at 4.5 t/ha vermicompost applied to previous sorghum/groundnut intercropping, while the lowest (1.02%) was obtained in the control plot (Fig 2A). A similar trend was seen in SOC (Fig 2A). Additionally, as the rate of vermicompost increased from nil to 4.5 t/ha under the intercropping system, the soil SOC increased by 51.28% and SOM by 88.2% (Fig 2A). Application of high vermicompost dosage reduces soil compaction by 8.61% than the control plot. The minimum soil BD (1.22 g/cm<sup>3</sup>) was recorded at 4.5 t/ha of vermicompost combined with the tied-ridge planting pattern (Fig 2C), while the maximum (1.45 g/cm<sup>3</sup>) was observed in monocropped sorghum without any treatments (Fig 2B). Increasing the rate of vermicompost decreased soil bulk density by 7.81% and 7.22% under both sowing methods and seedbed types compared to the corresponding control (Figs 2B and C).

**Soil pH, cation exchange capacity (CEC), and electrical conductivity (EC).** The main effects and two-way interactions of vermicompost and cropping systems significantly ( $P \leq 0.05$ ) affected soil pH, CEC, and EC (S3 Table in S1 File), while the three-way interaction effect and the two-way interaction effect between planting and seedbed types were insignificant (Table 3). Preliminary soil analysis shows that the soil pH is approximately 1.79% lower than the residual vermicompost at a rate of 3 t/ha in the second cropping season (Fig 3). Increasing the rates of vermicompost from nil to 3 t/ha under intercropping raised soil pH by 2.54%, but at 4.5 t/ha, it decreased by 0.76% (Fig 3). Likewise, soil pH increased with higher rates of vermicompost up to 3 t/ha by 2.02% and 2.68% under flat-bed and tied-ridge planting patterns, respectively, with a decreasing trend at the highest fertilizer dose (Fig 3). Consequently, the highest CEC (33.362 cmol (+)/Kg) was recorded at 4.5 t/ha of vermicompost under sorghum-groundnut intercropping, followed by the open-furrow planting at the same dose (Table 4). However, the opposite trend was observed for EC, which decreased significantly with the increased rate of vermicompost application, regardless of the combined sowing methods and seedbed types (Table 4).

Table 3. Second-year post-harvest mean squares of ANOVA of soil physico-chemical properties at Kile in 2022 cropping seasons.

Source of Variation	df	Organic carbon	Bulk density	pH	CEC	EC	Nitrogen(N)		Phosphorus (P)	Potassium (K)
SM	1	0.08 <sup>**</sup>	0.43 <sup>**</sup>	0.05 <sup>**</sup>	28.08 <sup>*</sup>	85.23 <sup>*</sup>	0.0019 <sup>*</sup>		1.62 <sup>*</sup>	0.14 <sup>**</sup>
SB	1	0.005 <sup>ns</sup>	0.13 <sup>**</sup>	0.025 <sup>*</sup>	8.68 <sup>ns</sup>	264 <sup>*</sup>	0.0004 <sup>ns</sup>		1.91 <sup>*</sup>	0.01 <sup>*</sup>
VC	3	1.19 <sup>**</sup>	0.05 <sup>**</sup>	0.27 <sup>**</sup>	422 <sup>**</sup>	2874 <sup>*</sup>	.054 <sup>**</sup>		77 <sup>**</sup>	1.15 <sup>**</sup>
SM*SB	1	0.001 <sup>ns</sup>	0.001 <sup>ns</sup>	0.01 <sup>ns</sup>	8.39 <sup>ns</sup>	11.19 <sup>ns</sup>	0.00 <sup>ns</sup>		0.01 <sup>ns</sup>	0.002 <sup>ns</sup>
SM*VC	3	0.03 <sup>*</sup>	0.01 <sup>**</sup>	0.02 <sup>*</sup>	43.6 <sup>**</sup>	47.11 <sup>*</sup>	0.001 <sup>**</sup>		0.38 <sup>*</sup>	0.04 <sup>**</sup>
SB*VC	3	0.001 <sup>ns</sup>	0.007 <sup>*</sup>	0.02 <sup>**</sup>	11.33 <sup>*</sup>	61.24 <sup>*</sup>	0.0007 <sup>*</sup>		0.62 <sup>*</sup>	0.003 <sup>ns</sup>
SM*SB * VC	3	0.001 <sup>ns</sup>	0.001 <sup>ns</sup>	0.003 <sup>ns</sup>	2.20 <sup>ns</sup>	11.69 <sup>ns</sup>	0.0002 <sup>ns</sup>		0.11 <sup>ns</sup>	0.001 <sup>ns</sup>
Errors	47	34.8	0.001	0.001	3.08	5.8	0.0001		0.11	0.002
CV (%)		5.56	5.86	5.88	7.93	5.52	7.77		5.87	7.01
Source of Variation	Df	Calcium (Ca)	Iron (Fe)	Zinc (Zn)	Manganese (Mn)	SMC1	SMC2	Striga Density	Stover-yield (t/ha)	Grain yield (t/ha)
SM	1	1.21 <sup>ns</sup>	61.6 <sup>*</sup>	0.12 <sup>**</sup>	0.62 <sup>**</sup>	83.9 <sup>**</sup>	31.23	60.55 <sup>**</sup>	2.76 <sup>*</sup>	1.14 <sup>**</sup>
SB	1	0.02 <sup>ns</sup>	7.23 <sup>ns</sup>	0.01 <sup>ns</sup>	0.07 <sup>ns</sup>	538 <sup>**</sup>	121 <sup>**</sup>	61.22 <sup>**</sup>	19.594 <sup>**</sup>	4.35 <sup>**</sup>
VC	3	194 <sup>**</sup>	21 <sup>**</sup>	3.65 <sup>**</sup>	0.21 <sup>**</sup>	244 <sup>**</sup>	148 <sup>**</sup>	97.38 <sup>**</sup>	70.94 <sup>**</sup>	23.21 <sup>**</sup>
SM*SB	1	1.43 <sup>ns</sup>	6.03 <sup>ns</sup>	0.13 <sup>**</sup>	0.06 <sup>ns</sup>	97.36 <sup>**</sup>	6.68 <sup>*</sup>	4.71 <sup>**</sup>	0.332 <sup>ns</sup>	0.3 <sup>ns</sup>
SM*VC	3	4.04 <sup>*</sup>	8.39 <sup>*</sup>	0.024 <sup>*</sup>	0.08 <sup>*</sup>	6.16 <sup>*</sup>	8.08 <sup>**</sup>	2.86 <sup>**</sup>	0.784 <sup>ns</sup>	0.05 <sup>ns</sup>
SB*VC	3	0.05 <sup>ns</sup>	0.07 <sup>ns</sup>	0.03 <sup>*</sup>	0.001 <sup>ns</sup>	35.75 <sup>**</sup>	8.42 <sup>**</sup>	2.78 <sup>**</sup>	1.083 <sup>*</sup>	0.52 <sup>*</sup>
SM*SB * VC	3	1.62 <sup>ns</sup>	1.8 <sup>ns</sup>	0.017 <sup>*</sup>	0.02 <sup>ns</sup>	10.42 <sup>*</sup>	9.63 <sup>**</sup>	1.36 <sup>**</sup>	1.787 <sup>*</sup>	0.29 <sup>*</sup>
Errors	47	0.87	2	0.004	0.02	1.80	1.23	0.13	0.362	0.08
CV (%)		6.59	6.87	6.01	6.87	6.73	7.03	7.05	9.668	8.89

df= degree of freedom; ns = not significant;

\* and

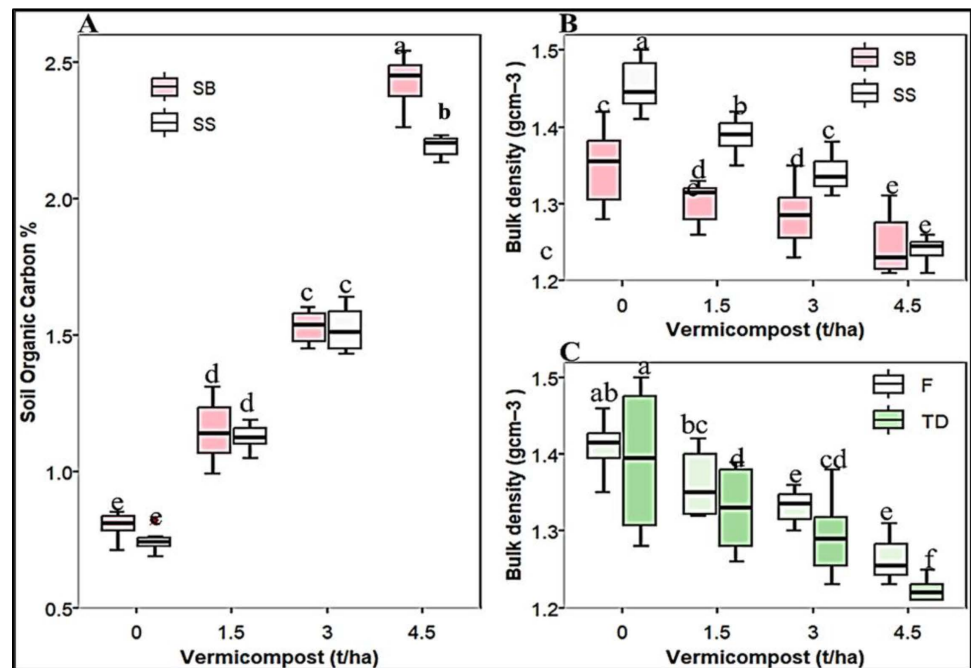
\*\*= significant at 5% and 1% probability levels, respectively. CEC = cation exchangeable capacity; EC = electric conductivity; SMC = soil moisture content at vegetative (1) and reproductive stage (2); sowing methods (SM); seedbed type (SB); VC = vermicompost; CV = coefficient of variation.

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**Total nitrogen (N) and available phosphorus (P).** The results in Table 3 showed that total nitrogen and available Olsen P were significantly ( $P < 0.05$ ) influenced by the two-way interaction and main effects of vermicompost and cropping systems. However, seedbed types, either individually or in interaction with both factors, did not significantly affect soil N and P (Table 3). Treatments previously amended with 4.5 t/ha of vermicompost under the sorghum-groundnut intercrop system resulted in the highest total N (0.242%) and available P (9.822 mg/Kg) (Table 5). Whereas the control plot (unamended soil) gave the lowest total N (0.007%) and Olsen P (3.57 mg/Kg). Compared to solely cropped sorghum at nil fertilizer, the previous intercropped sorghum-groundnut system increased soil N and P by about 8.69% and 4.75%, respectively, when it was treated with 4.5 t/ha vermicompost (Table 5). Except for the plot that received the highest vermicompost rate, all plots that received the same rate in both intercropping and monocropped systems were statistically insignificant from each other for N and P (Table 5).

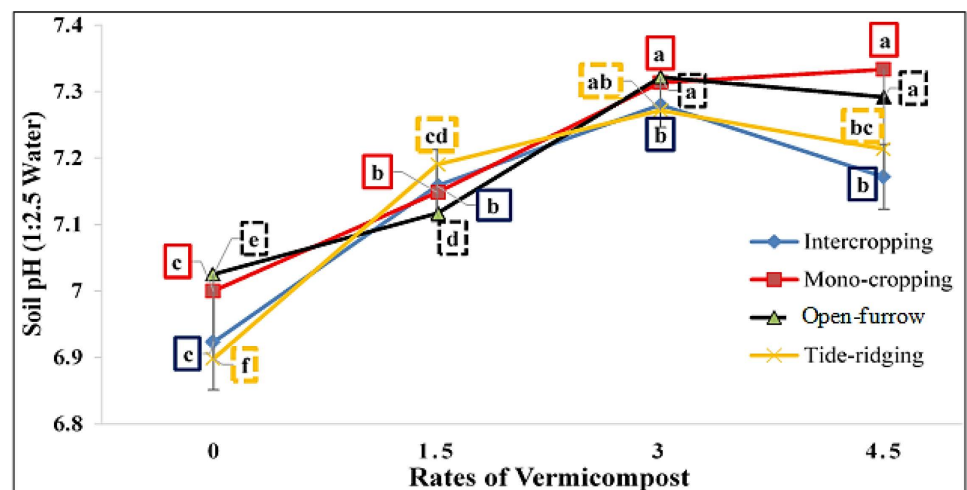
**Exchangeable bases (K, Ca, and Mg).** Single and joint applications of vermicompost and sowing methods were significant ( $P < 0.05$ ) for exchangeable bases (S4 Table in S1 File). However, exchangeable Ca was not significantly affected by a single effect of cropping and seedbed types, unlike other bases (Table 3). The highest values for all exchangeable bases were obtained in plots treated with 4.5 t/ha vermicompost under an intercropping scheme (Fig 4). The study revealed that the minimum exchangeable bases in sorghum grown in monocultures without vermicompost and intercropped with nil fertilizer were statistically identical to those in plots receiving 1.5 t/ha of vermicompost. In the intercropping system at 4.5 t/ha





**Fig 2.** Joint interaction effect of vermicompost and planting methods on soil organic carbon (A) and bulk density (B), as well as two-way interaction effect of vermicompost and seedbed types on soil BD (C); “SS,” “SB,” “F,” and “TD” stand for “sole sorghum,” “intercropped sorghum with groundnut,” “flat bed,” and “tied ridge,” respectively. Boxes sharing the same letter under each figure were statistically similar.

<https://doi.org/10.1371/journal.pone.0318057.g002>



**Fig 3.** Two-way interaction effect of vermicompost and planting methods on soil pH. Line sharing the same letter was statistically similar.

<https://doi.org/10.1371/journal.pone.0318057.g003>

vermicompost, the concentration of exchangeable K, Mg, and Ca increased linearly by 64.18%, 25%, and 37.31%, respectively (Fig 4A–C).

**Extractable zinc (Zn), iron (Fe), and manganese (Mn).** The combined application of vermicompost with different sowing methods had a significant residual effect on extractable micronutrients (Fe, Mn, and Zn) (Table 3). The mean effect of all three factors was significant

Table 4. Residual effect of vermicompost and cropping systems on soil EC and CEC in 2022 years at Kile.

Vermicompost (t/ha)	Electric conductivity (dS/cm)				Cation exchange capacity (cmol (+)/Kg soil)			
	Intercrop	Monocrop	F	TD	Intercrop	Monocrop	F	TD
0	63.517 <sup>a</sup>	61.813 <sup>a</sup>	67.94 <sup>a</sup>	57.39 <sup>b</sup>	15.092 <sup>e</sup>	16.337 <sup>e</sup>	15.31 <sup>e</sup>	16.12 <sup>e</sup>
1.5	54.077 <sup>b</sup>	45.637 <sup>c</sup>	52.73 <sup>c</sup>	46.98 <sup>c</sup>	19.815 <sup>d</sup>	20.167 <sup>d</sup>	20 <sup>d</sup>	19.98 <sup>d</sup>
3	32.933 <sup>d</sup>	31.883 <sup>de</sup>	33.47 <sup>c</sup>	31.35 <sup>ef</sup>	23.398 <sup>c</sup>	22.822 <sup>c</sup>	23.38 <sup>c</sup>	22.84 <sup>c</sup>
4.5	30.063 <sup>de</sup>	29.53 <sup>c</sup>	29.96 <sup>f</sup>	29.64 <sup>f</sup>	33.362 <sup>a</sup>	26.223 <sup>b</sup>	31.62 <sup>a</sup>	27.97 <sup>b</sup>
LSD	3.004				2.332			

TD = tied-ridge; F = open-furrow (traditional practice); LSD = least significant difference. Means sharing the same letters under each variable was non-significant.

<https://doi.org/10.1371/journal.pone.0318057.t004>

Table 5. Residual effect of vermicompost and cropping systems on soil N and P in 2022 years at Kile.

Vermicompost (t/ha)	Total Nitrogen (N%)				Available Phosphorus (Olsen P mg/Kg)			
	Intercrop	Monocrop	F	TD	Intercrop	Monocrop	F	TD
0	0.008 <sup>ef</sup>	0.007 <sup>f</sup>	0.008 <sup>e</sup>	0.009 <sup>e</sup>	3.868 <sup>e</sup>	3.573 <sup>e</sup>	3.748 <sup>f</sup>	3.693 <sup>f</sup>
1.5	0.093 <sup>de</sup>	0.099 <sup>d</sup>	0.094 <sup>d</sup>	0.098 <sup>d</sup>	4.762 <sup>d</sup>	4.582 <sup>d</sup>	4.727 <sup>e</sup>	4.617 <sup>e</sup>
3	0.135 <sup>c</sup>	0.125 <sup>c</sup>	0.13 <sup>c</sup>	0.13 <sup>c</sup>	7.04 <sup>c</sup>	6.935 <sup>c</sup>	7.457 <sup>c</sup>	6.518 <sup>d</sup>
4.5	0.247 <sup>a</sup>	0.208 <sup>b</sup>	0.242 <sup>a</sup>	0.213 <sup>b</sup>	9.822 <sup>a</sup>	8.93 <sup>b</sup>	9.677 <sup>a</sup>	9.075 <sup>b</sup>
LSD	0.014				0.495			

TD = tied-ridge; F = open-furrow planting pattern; LSD = least significant difference. Means sharing the same letters under each variable were non-significant.

<https://doi.org/10.1371/journal.pone.0318057.t005>

for Zn, while for Mn and Fe, only the single effects of sowing methods and vermicompost showed significant differences. Increasing rates of vermicompost under intercropping increased Zn and Fe by 40.1% and 27.15%, respectively (Table 6). However, Mn decreased by 2.56% with increased vermicompost rates. The lowest Mn (1.97 mg/Kg soil) was found at 4.5 t/ha in monocropped sorghum, which was statistically similar to the plot that received 1.5 t/ha. On the other hand, the highest mean values of extractable Fe (6.37 mg/Kg) and Zn (1.45 mg/Kg) were recorded at 4.5 t/ha of vermicompost under the intercropping system (Table 6).

**Soil moisture content (SMC).** The ANOVA results in Table 3 indicate a significant difference ( $P < 0.05$ ) among all treatment combinations in SMC during the 2022 cropping season. The highest SMC levels (>26.72%) at both stages were observed in tied-ridging under the intercropping system (Table 6). Specifically, the maximum SMC under tied-ridging at 4.5 t/ha exceeded the control plot by 47% and 46% at the vegetative and reproductive stages, respectively. Conversely, the lowest SMCs were found in both sole sorghum and previously intercropped sorghum without fertilizer (Table 7). Tied-ridge planting increased SOM by 16.13% in previously groundnut-intercropped fields at the vegetative stage and by 16.67% in sole cropping of sorghum at the reproductive stage without fertilizer application (Table 7). The SMC recorded at the early flowering stage generally exhibited a declining trend, which was more pronounced in treatments employing openfurrow (Table 7), likely due to the typically reduced rainfall during the critical reproductive stage (mid-September-November) in the study area (Fig 1).

**Residual effect of vermicompost and groundnut on *Striga* density.** The ANOVA result in Table 3 depicts the main effect as well as the combination effect of all factors significantly ( $P \leq 0.01$ ) affecting *Striga* density (S5 Table in S1 File). The highest *Striga* density (12.9 plants/plot) was observed in monocropped sorghum under the traditional tillage system and was significantly different from the other treatments (Fig 5). The minimum *Striga* density (1.09 plants/plot) was recorded at 4.5 t/ha of residual vermicompost applied under tied-ridging in

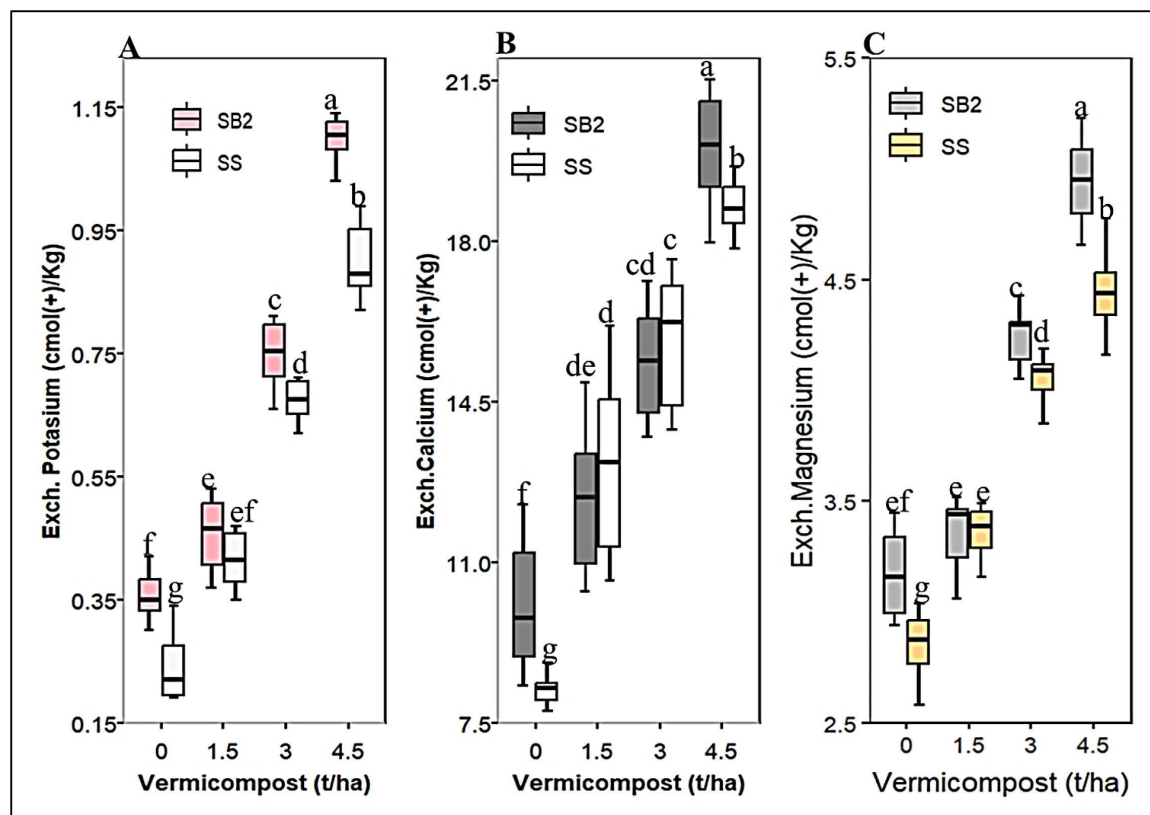


Fig 4. Two-way interaction effect of vermicompost and planting methods on soil Exch. Potassium (A), Exch. calcium (B), and Exch. Magnesium (C). Box sharing the same letter under each figure was statistically similar.

<https://doi.org/10.1371/journal.pone.0318057.g004>

Table 6. Interaction effect of vermicompost and sowing methods on Zn, Fe, and Mn in 2022 years at Kile.

Vermicompost (t/ha)	Zn (mg/Kg)		Fe (mg/Kg)		Mn (mg/Kg)	
	Intercrop	Monocrop	Intercrop	Monocrop	Intercrop	Monocrop
0	0.62 <sup>f</sup>	0.28 <sup>g</sup>	3.65 <sup>f</sup>	3.73 <sup>f</sup>	2.01 <sup>bcd</sup>	2.47 <sup>a</sup>
1.5	0.86 <sup>d</sup>	0.74 <sup>e</sup>	4.17 <sup>e</sup>	4.22 <sup>e</sup>	1.98 <sup>cd</sup>	2.16 <sup>b</sup>
3	1.18 <sup>b</sup>	1.08 <sup>c</sup>	5.16 <sup>c</sup>	4.72 <sup>d</sup>	1.89 <sup>d</sup>	2.08 <sup>bc</sup>
4.5	1.45 <sup>a</sup>	1.18 <sup>b</sup>	6.37 <sup>a</sup>	5.7 <sup>b</sup>	1.90 <sup>d</sup>	1.97 <sup>cd</sup>
LSD	0.08		0.38		0.18	

LSD = least significant difference; Zn = zinc; Fe = iron; Mn = manganese. Means sharing the same letters under each variable were non-significant.

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the previous intercropping system, at par with sole-cropped sorghum at the same treatment combinations. Increased vermicompost from nil to 4.5 t/ha declines *Striga* density by about 64 and 71% in monocropped and intercropped sorghum (Fig 5).

**Sorghum stover yield and grain yield.** Residual vermicompost under both cropping systems substantially affects both yield parameters of sorghum (Table 2). Accordingly, the highest stover yield (10.95 t/ha) was recorded under tied-ridge with *Babile-1* at 4.5 t/ha vermicompost, while the lowest sorghum grain yield (3.213 t/ha) was attained under control (sole cropped without fertilizer) (Table 8a). In comparison to the control plot (SSF), the application of vermicompost at 4.5 t/ha under previous intercropped groundnut

Table 7. Interaction effect of vermicompost, seedbed type, and cropping systems on soil moisture content (SOM) during the 2022 year at Kile.

Treatments	Soil moisture (%) at vegetative stage				Soil moisture (%) at reproductive stage			
	0	1.5	3	4.5	0	1.5	3	4.5
SSF	12.99 <sup>b</sup>	15.45 <sup>g</sup>	18.16 <sup>ef</sup>	20.23 <sup>cde</sup>	9.99 <sup>k</sup>	12.76 <sup>ij</sup>	14.91 <sup>gh</sup>	17.44 <sup>cde</sup>
SSTd	16.22 <sup>fg</sup>	18.36 <sup>ef</sup>	20.65 <sup>cd</sup>	26.99 <sup>b</sup>	14.05 <sup>ghi</sup>	15.12 <sup>fg</sup>	16.06 <sup>ef</sup>	19.57 <sup>b</sup>
SS1F	13.11 <sup>b</sup>	15.61 <sup>g</sup>	18.01 <sup>ef</sup>	19.19 <sup>de</sup>	11.21 <sup>kj</sup>	13.24 <sup>hi</sup>	16.16 <sup>def</sup>	17.96 <sup>bcd</sup>
SS1Td	18.15 <sup>ef</sup>	21.89 <sup>c</sup>	28.39 <sup>b</sup>	35.75 <sup>a</sup>	13.96 <sup>ghi</sup>	15.05 <sup>gh</sup>	18.51 <sup>bc</sup>	26.72 <sup>a</sup>
LSD	2.64				1.84			

SSF/Td = sole sorghum under present F = open-furrow; Td = tied ridge; SS1F/Td = previous intercropped sorghum with *Babille-1* under open-furrow (F) and tied ridge (Td), respectively; VC = vermicompost; LSD = least significant difference. Mean sharing the same letter are insignificantly different.

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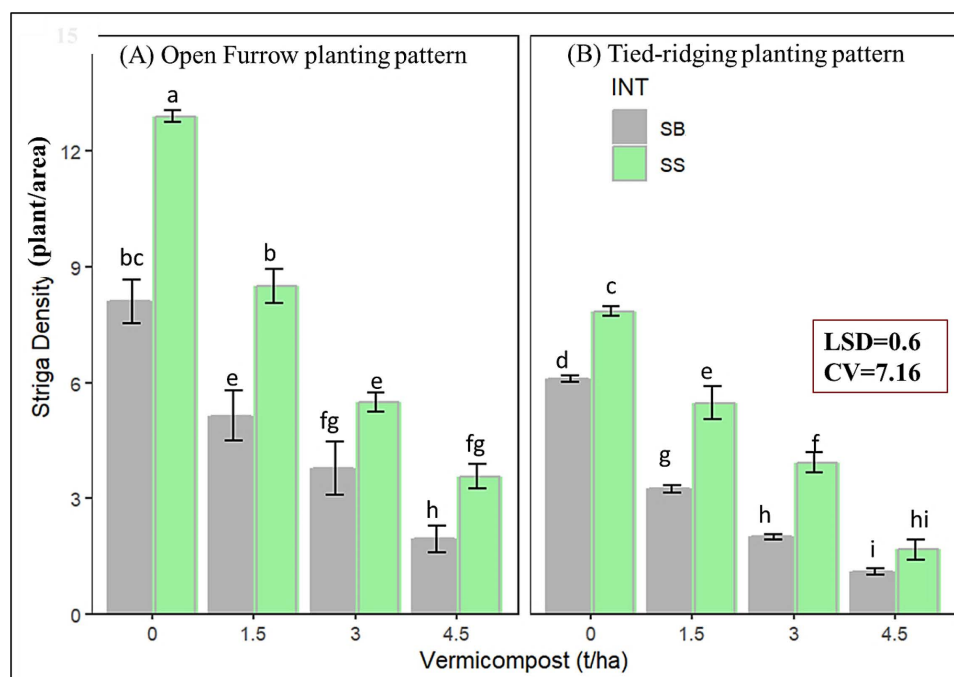


Fig 5. Three-way interaction effect of all factor on *Striga* density; LSD =Least significant difference; CV=Coefficient of variation. Bar sharing the same letter under each figure were statistically similar.

<https://doi.org/10.1371/journal.pone.0318057.g005>

boosted stover yield by 54% (Table 8a). Likewise, the greatest sorghum grain yield (5.817 t/ha) recorded at 4.5 t/ha residual vermicompost with a tied-ridge planting pattern was nearly three times more than the control plot (Table 8b). Compared to pure-stand sorghum without fertilizer, residual vermicompost application at 4.5 t/ha in an intercropping system enhanced grain yield by 57.47% (Table 8b).

## Discussion

### Properties of vermicompost and soil before experiment

The high concentration of organic matter in vermicompost may be attributed to the abundance of biomass found in *Lantana camara* and animal feces, which act as substrates. The higher EC of vermicompost compared to pre-sowing soil is most likely due to increased

**Table 8. Residual effect of vermicompost under previous intercropping and both seedbed types on sorghum stover yield and grain yield at Kile during the 2022 year.**

Cropping pattern	(a) Stover yield (t/ha)					(b) Grain yield (t/ha)			
	Residual VC (t/ha)	0	1.5	3	4.5	0	1.5	3	4.5
SSF		3.213 <sup>c</sup>	3.9474 <sup>c</sup>	5.804 <sup>d</sup>	8.073 <sup>b</sup>	1.445 <sup>f</sup>	2.538 <sup>e</sup>	3.264 <sup>d</sup>	4.162 <sup>c</sup>
SSTd		3.766 <sup>e</sup>	6.018 <sup>cd</sup>	8.206 <sup>bc</sup>	8.206 <sup>b</sup>	1.627 <sup>f</sup>	2.436 <sup>e</sup>	3.839 <sup>e</sup>	5.285 <sup>a</sup>
SS1F		3.49 <sup>e</sup>	5.28 <sup>d</sup>	6.852 <sup>c</sup>	8.339 <sup>b</sup>	1.503 <sup>f</sup>	2.49 <sup>e</sup>	3.236 <sup>d</sup>	4.782 <sup>b</sup>
SS1Td		3.59 <sup>e</sup>	5.49 <sup>d</sup>	8.178 <sup>b</sup>	10.81 <sup>a</sup>	2.291 <sup>e</sup>	2.728 <sup>e</sup>	4.68 <sup>b</sup>	5.35 <sup>a</sup>
LSD		1.0				0.082			

SSF/Td = sole sorghum under present F = open-furrow; Td = tied ridge; SS1F/Td = previous intercropped sorghum with Babile-1 under open-furrow (F) and tied ridge (Td), respectively; VC = vermicompost; LSD = least significant difference. Mean sharing the same letter are insignificant.

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soluble salts in vermicompost following worm activity [36]. Vermicompost has the optimum nutrient C:N ratio and high-status accessible nutrients used for plant growth [20,77]. This high OM and CEC content in vermicompost was most likely responsible for the higher levels of macro- and micronutrients [21,36].

The soil in the research area has a sandy loam texture with 66.78% sand and 15.06% clay content, making it ideal for sorghum and groundnut production. However, according to Wogi *et al.* [78], the soils in the research area are extremely deficient in soil N, P, K, SOM, and other nutrients. Similarly, the maximum soil bulk density (1.45 g/cm<sup>3</sup>) in Kile may be attributable to excessive compaction from extensive sorghum monocropping and constant tractor use. These issues highlight the need for using high-quality organic fertilizer (vermicompost), which has a significantly higher concentration of SOM and most importantly plant nutrients than soil. This could rectify the plant nutrient imbalance and increase productivity without endangering the agroecosystem [78,79].

### Residual effect of vermicompost and groundnut on selected soil physico-chemical characteristics in sorghum field at Kile in 2022 year

**Soil organic carbon (SOC), bulk density (BD), and moisture content (SMC).** Vermicompost is an excellent soil conditioner that can aid in environmentally friendly farming practices. The SMC increased in plots with tied-ridging, groundnut intercropping, and vermicompost treatment, possibly due to lower bulk density and higher SOC levels from previous years. Bekele & Chemeda [80] found that tied ridging increased soil water and sorghum grain yield by more than 25% and 40%, respectively, compared to regular tillage in northern Ethiopia. Abie *et al.* [81] observed that plots treated with tied ridges had higher soil moisture content than the control plot. In addition, the organic matter in vermicompost binds soil particles together to form stable, larger aggregates with holes, lowering bulk density and improving water retention by slowing surface water flow [64]. The lower soil BD and linear increase in SOC are most likely due to a higher fraction of SOM return from groundnut biomass [82]. Similarly, a large surface area and low C/N ratios of vermicompost speed up decomposition, boosting SOM while decreasing soil bulk density [83]. In sandy soils, high SOM and low BD increase soil water-holding capacity, besides improving soil physicochemical features [24]. Bhanwaria *et al.* [20] also reported that applying 5 t/ha of vermicompost increased soil moisture retention and accessible soil water in mustard crops under stress in arid environments. Bhanwaria *et al.* [20]; Hafez *et al.* [50]; and Demir [84] additionally endorsed our findings, stating that soil organic matter is a significant source of accessible nutrients, soil water-holding capacity, and CEC that maintain soil stability. According to research by Angelova *et al.* [85], adding 5 and 10 grams of vermicompost to soil



boosted its organic content by 3.99% and 9.36%, respectively. According to González *et al.* [18], vermicompost applied once at a dose of 2 kg m<sup>-2</sup> was enough to significantly lower the bulk density of the soil. Atspha *et al.* [86] and Li *et al.* [87] conveyed comparable findings.

Our research findings about intercropping also aligned with those of Roohi *et al.* [6], Talababie *et al.* [88], and Nasar *et al.* [89], who found that intercropped maize with high biomass and litter production had the maximum amount of soil organic matter. Attallah *et al.* [90] found that when compared to monocropping, intercropping durum wheat with chickpeas increased soil carbon levels. A higher SOC results from microbial activity in the soil breaking down vermicompost and residual intercropping, which promotes soil fertility and carbon sequestration [6,91]. Increased groundnut and sorghum litter results in a larger SOM stock, which increases the amount of labile carbon [56]. This illustrates the necessity of using tied-ridge planting patterns and vermicompost to maintain optimal SMC levels, improve soil fertility, and reduce irrigation frequency.

**Soil pH.** The slight increase in soil pH in residual vermicompost could be attributed to the high pH and basic cations contained in vermicompost [92,93]. However, the increased release of H<sup>+</sup> ions from groundnuts caused by N<sub>2</sub>-fixation, excessive cation absorption, and root exudation of organic acids significantly reduces soil pH in the intercropping system [94,95]. This proves that the combined application of vermicompost and intercropping systems aids in buffering soil pH within the range that is optimal for crop growth and the availability of plant nutrients [85,96–98]. Additionally, vermicompost can neutralize excessive acidity or alkalinity in soil, hence buffering its pH [90]. This finding is consistent with Bhanwaria *et al.* [20] and Adebayo *et al.* [92], who revealed that residual vermicompost raised soil pH, SOC, P, and K levels. According to Wegene *et al.* [98], the use of vermicompost increased soil pH from 5.1 to 5.5 due to humic chemicals produced during H<sup>+</sup>-consuming decomposition processes. Beshir & Abdulkerims [9] noted that the pH of the soil was lower when the intercropping was done with a closed-end tied ridge. The observed lower soil pH in the tied-ridge planting pattern may be due to proton generation linked to nitrification, as lower redox potential is generally reported in saturated or wet soil [99]. Nasar *et al.* [89]; Guerchi *et al.* [95]; and Saha *et al.* [100] found similar results in cereal-legume intercropping.

**Cation exchange capacity (CEC) and electric conductivity (EC).** The results of the study indicate that the addition of vermicompost and groundnut intercropping has a considerable impact on the soil CEC and EC, probably due to an increase in soil OM content. Increased soil organic matter and the formation of additional phenolic and carboxylic functional groups could explain the rise in CEC [101,102]. High CEC increases nutrient availability for plant development by reducing leaching [103,104]. The soil EC may have decreased due to vermicompost's high sorption capacity, which allows it to absorb a large amount of salts and amino acids created during microbial decomposition [93,105]. Similar outcomes were found by Bhanwaria *et al.* [20], who reported that a decrease in soil pH and EC led to a decrease in soil salinity and an improvement in soil quality. According to Guerchi *et al.* [95], intercropping sea and alfalfa hardly lowers soil salinity in arid and semi-arid areas, which supports sustainable farming practices.

**Total nitrogen (N) and available phosphorus (P).** The highest residual soil N and P levels in the second year are most likely caused by a high rate of higher total organic C and N return from vermicompost as well as greater groundnut leaf drop along with a significant amount of fixed nitrogen throughout the growth season [29]. Soils treated with vermicompost were more likely to resist nutrient immobilization and retain more accessible N and P at the end of the growth cycle due to the greater availability of organic matter [91]. Additionally, vermicompost reduces the P fixation and enhances the P mobilization via its rich organic acids, which compete for binding sites with orthophosphates and complexes with metals,

thereby slowing down the formation of sparingly soluble phosphates [97]. The current finding has been supported by Jat & Ahlawat [25], Angelova *et al.* [85], and Mengistu *et al.* [106], who reported that vermicompost outperformed the control treatment in terms of available and total N. Similar to this, Talababie *et al.* [88] discovered a rise in soil P and N levels during the first season of a legume-cereal intercropping system.

Intercropping improved the microclimate, biomass returned to the soil (exudates, root debris, and leaf shade), and soil microbial activity [58], all of which accelerated the breakdown of resistant carbon such as cellulose and lignin [54] soil-based N, P, K,  $\text{NH}_4$ ,  $\text{NO}_3$ , and SOC [89]. According to the Ncube *et al.* [107] study, groundnut and cowpea legumes accumulated up to 130 kg of nitrogen per hectare, which sorghum may absorb in the following season. Intercropped groundnut fixed the highest amount of nitrogen from the atmosphere and transferred 12–26% more nitrogen to base crops than cowpea (*Vigna unguiculata* L.) and mungbean (*Vigna radiata* L.) [108].

The residual Olsen P in the second year at 4.5 t/ha, vermicompost exhibits the lowest range, demonstrating definitely the need for additional P fertilizer for the crop the following year. This could have been brought on by microbial immobilization [61] high adsorption of P to leftover Ca, Mg, and K [109] or significant P removal from the soil through harvested materials. However, the residual effect of total N in vermicompost was classified as high to very high at 3 and 4.5 t/ha [78]. It would be able to gain the benefits of large doses of vermicompost for more than two successive cropping. When cassava and peanuts were interplanted for three years in a row, accessible N, P, K, and organic matter rose by 40% and nearly 20 times, respectively, compared to the control soils [110].

**Exchangeable bases (K, Ca, and Mg).** The greatest number of exchangeable bases identified at high vermicompost dosages were linked to high CEC, which had a significant buffering capacity and the ability to hold cations against leaching [106,111]. These findings are consistent with those of Demir [84], who discovered that raising the vermicompost rate significantly increased the exchangeable base K, Mg, and Ca levels in the soil. Vermicompost increases potassium, exchangeable magnesium, accessible phosphorus, and SOM [112]. Organic amendments increased soil exchangeable K, Mg, Ca, and CEC [113]. Maize-haricot bean intercropping improved the likely availability of potassium in the soil after planting [9]. The soil exchangeable Ca and Mg levels ranged from high to extremely high, according to the Wogi *et al.* [78] rating. This shows that additional soil inputs are unnecessary because the agricultural soils in this area do not suffer from calcium and magnesium deficits. However, residual exchangeable K decreased, necessitating further K-containing fertilizer inputs. Intercropping improved soil physicochemical properties by boosting ecosystem functioning, such as soil microbial biomass, enzyme activity, and nutrient cycling [58].

**Extractable zinc (Zn), iron (Fe), and manganese (Mn).** Vermicompost often contains more nutrients than conventional compost produced from the same substrate because earthworms digest and fragment the material in biochemical form, adding vitamins, antibiotics, enzymes, and growth hormones [96]. Increased soil organic carbon and pH were most likely accountable for the highest extractable Zn and Fe levels in the previously treated plot with high vermicompost dosage. Furthermore, the application of vermicompost could stimulate the growth of the Fe-reducing microorganisms, which have a synergistic effect with OM, thereby enhancing Fe reduction [97]. These findings were consistent with Demir [84], who reported an increasing trend in the micronutrients (Fe, Mn, Zn, and Cu) in vermicompost with different watering regimens. The macronutrient and micronutrient content of the postharvest soil within the cauliflower field increased as vermicompost application doses increased [114]. Mengistu *et al.* [106] found that the high organic matter content of vermicompost enhances micronutrient concentrations (Fe, Mn, Zn, and Cu) in

soil through oxidation and decomposition. Nevertheless, our results show that extractable Mn levels decreased as vermicompost levels increased. This could be linked to a rise in soil pH, which could lead to the development of low-solubility compounds and better soil colloidal retention [115]. Mn shortages caused by high vermicompost rates have been connected to low Mn and high SOM, which firmly contained it [116]. In contrast, because Zn is not strongly linked to organic materials, its availability increases.

### Residual effect of vermicompost on *Striga* density and associated sorghum yield

***Striga* density.** The decline in *Striga* density under the highest fertilizer dose could be linked to the lower C:N ratio as well as the high NPK and SOM content of vermicompost [86]. Furthermore, the addition of vermicompost significantly improved post-harvest soil microbial activity and important nutrients [21,117]. Another aspect could be improved availability of minerals such as zinc, boron, and magnesium, which help to create mechanical barriers (lignification or phenolic compounds) and hence improve host-plant resilience in the post-attachment stages [16,17]. The result aligned with the findings of Gacheru & Rao [118], who discovered that organic residues can reduce *Striga* seed germination and viability. Goldwasser & Rodenburg [119] discovered that the breakdown of organic components in an intercropping system results in nutrient release, enhanced biological activity, and the generation of ethylene gas, causing *Striga* to germinate. *Striga* emergence, attachments, and germination were reduced when the host plant reduced strigolactone exudation [120,121].

Furthermore, vermicompost decomposition [22,32] resulted in plant growth regulators, increased microbial populations and activities [69], and increased host-plant resistance to pest attacks [91]. Likewise, Woldemariam & Damot [122] explored the management of animal manure and nitrogen. Restore biomass productivity to rejuvenate and rebuild soil. Under legume cultivation, soil organic carbon content increased and the number of *Striga* seeds per square meter decreased (Abunyewa & Padi, 2003) [123]. Tesso & Ejeta [14] noted that tied-ridge tillage reduced the number of emerged *Striga* by two to three times at the last scoring dates as well as significantly lowering *Striga* vigor. Cereal-legume intercropping also shelters the soil from direct sunshine, reducing evaporation and increasing soil water retention for plant uptake [9].

**Sorghum yield.** The findings revealed that residual vermicompost at 4.5 t/ha yielded the highest sorghum yield, most likely due to significant nutrient storage and reservation at this rate. Improved nutrient availability and soil structure influenced plant vegetative development and yield characteristics [124]. According to a meta-analysis of Mak-Mensah *et al.* [125] and a finding of Mesfin *et al.* [74], the tied-ridge planting pattern had a yield advantage over flat planting for sorghum of more than 17%. Tie-ridging may boost sorghum grain output by making better use of the retained soil moisture, soil organic carbon, and total nitrogen. Tied-ridging may boost sorghum grain yield by making better use of the retained soil moisture, soil organic carbon, and total nitrogen. Adebayo *et al.* [92] reported similar results that residual vermicompost boosted cucumber (*Cucumis sativus* L.) production in the following plantings. Furthermore, by enhancing N, P, and K uptake, the residual application of farmyard manure plus 75% NPK increased wheat grain yield considerably [124]. Dass *et al.* [126] revealed that the cumulative influence of earlier black-gram intercropping significantly increased the growth and productivity of the current wheat crop. Peanut and maize intercropping affected the composition of soil microorganisms that aid in plant development and nutrient uptake [127]. Hence, such integrated practice could provide a comprehensive way to produce sorghum while improving soil fertility and reducing *Striga* infestation.

## Conclusion

The results revealed that soil organic carbon (SOC), nitrogen (N), calcium (Ca), magnesium (Mg), zinc (Zn), and iron (Fe) levels linearly increased with the application rate of vermicompost under an intercropping system. The soil moisture content (SMC) also had a significant increase in both sorghum growth stages due to the residual effect of vermicompost under a tied-ridge planting pattern. The combined application of high vermicompost and tied-ridge in preceding intercropped groundnut gave the highest sorghum yields by decreasing *Striga* infestation. Hence, preceding groundnut intercropping and residual vermicompost not only improve soil fertility and moisture retention but also reduce *Striga* density, thereby offering promising prospects for sustainable sorghum production in the semi-arid regions of the eastern Hararghe zone. The aforementioned treatment showed a slight decline in soil pH, electrical conductivity (EC), and bulk density (BD), as well as available phosphorus (P) and potassium (K), compared to the initial soil analysis result but higher than the current control plot. This indicates depletion of P and K after the second planting, which suggests residual effects of vermicompost were sufficient for one planting cycle for P and K. However, other soil nutrients left in the soil system after the second cropping season ranged between medium and high at 4.5 t/ha of vermicompost, henceforth might be available for the third cropping cycle. Similarly, monocropped sorghum without fertilizer exhibited the lowest levels of macro- and micronutrients, attributed to the intensive nutrient uptake by sorghum over two years. This greatly benefits smallholder farmers in terms of economic return, ecological safety, and nutritional quality, particularly from groundnut.

## Supporting information

**S1 File.** S1 Table. Soil pH as influenced by Vermicompost with cropping systems [seedbed types (A) and sowing methods (B)]. S2 Table. Soil organic carbon (SOC) as influenced by Vermicompost with sowing methods. S3 Table. Potassium (K) as influenced by Vermicompost with sowing methods. S4 Table. Soil Calcium (Ca) as influenced by Vermicompost with sowing methods. S5 Table. Soil Magnesium (Mg) as influenced by Vermicompost with sowing methods. S6 Table. *Striga* density as influenced by Vermicompost with cropping systems. (DOCX)

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