Environmental Challenges 16 (2024) 101007

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Sustainable weed management and soil enrichment with water hyacinth composting and mineral fertilizer integration

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ARTICLE INFO

Keywords:
Composting
Crop production
Invasive weed
Soil fertility
Waste management

ABSTRACT

Composting water hyacinth (*Eichhornia crassipes*) presents a promising approach for managing the weed and the aquatic environment while increasing agricultural production and soil fertility. However, limited research reported on the impact of water hyacinth compost on soil properties and crop production under field conditions. This study aimed to evaluate impact of water hyacinth compost and its combined application with mineral fertilizer on soil properties and crop production. Before field experiments, the compost's phytotoxicity was assessed through bioassays, confirming it was safe for agricultural use with a seed germination index exceeding 80 %. Field trials were conducted using a factorial design with four application rates of water hyacinth compost (0, 8, 16, and 24 t ha^{-1}) and three rates of the recommended mineral fertilizer for teff production (0/0, 40/23, and 80/46 kg N/P_2O_5 ha^{-1}). The results indicated that compared to the control group, applying water hyacinth compost increased soil pH by up to 0.69 units and reduced bulk density by 10.3 %. Soil organic carbon, total nitrogen, available phosphorus, cation exchange capacity, and exchangeable potassium increased by 24.3 %, 28.6 %, 80.2 %, 26.2 %, and 112.7 %, respectively. Furthermore, exchangeable acidity and aluminum were reduced by 72.5 % and 78.6 %, respectively. The maximum grain yield (1826 kg ha^{-1}) and total biomass (8020 kg ha^{-1}) of teff were achieved by applying 24 t ha^{-1} of water hyacinth compost coupled with the full rate of mineral fertilizer. However, compared to adding only full fertilizer, the grain yield that resulted from applying water hyacinth compost at 16 and 24 t ha^{-1} along with half of the suggested mineral fertilizer was superior. This implies that water hyacinth compost could substitute 50 % of the mineral fertilizer required. In conclusion, composting water hyacinth offers a dual benefit of weed management and soil enrichment. This could be a sustainable strategy to mitigate weed proliferation while improving soil quality and crop production.

1. Introduction

Managing the disposal of solid waste has become one of the most significant societal challenges of our time (Barles, 2014). Composting, one of the most effective treatment methods for removing the organic components of solid waste (Levis et al., 2010), plays a crucial role in managing landfills by recycling and reusing organic wastes, thereby reducing the overall amount of waste generated (Ahmad et al., 2021). In addition to reducing the environmental impacts of chemical fertilizer manufacturing and use (Jain and Kalamdhad, 2020) and the cost associated with buying chemical fertilizers (Hernández et al., 2016), composting is a practical solution for transforming organic wastes into valuable organic fertilizer and soil conditioner, which helps to improve soil quality and promote sustainable crop production (Nigussie et al.,

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https://doi.org/10.1016/j.envc.2024.101007
Received 27 July 2024; Received in revised form 31 August 2024; Accepted 4 September 2024

2021; Soudek et al., 2024). Compost can alleviate soil fertility problems by improving soil structure, nutrient retention, water-holding capacity, cation exchange capacity (CEC), microbial activity, and ultimately enhancing crop productivity to reduce food insecurity (Phares and Akaba, 2022).

In sub-Saharan Africa (SSA), food insecurity, hunger, and poverty are believed to be primarily caused by land degradation, deforestation, desertification, and declining soil fertility (Bado and Bationo, 2018). Ethiopia, one of the SSA countries, has faced big challenges due to a growing population along with unsustainable farmland management practices, leading to reduced soil fertility (Amsalu et al., 2007) and a decline in agricultural yields (Haileslassie et al., 2005; Dessie et al., 2023). The soils in the Ethiopian highlands are poor in organic matter and lack major macro- and micronutrients (Elias, 2016). Preserving soil fertility in the country often involves applying mineral fertilizers but at low rates (Elias et al., 2019). However, the resource-limited farmers in the Ethiopian highlands often cannot afford to purchase fertilizers at the recommended rates (Karltun et al., 2011). As a result, integrated soil fertility management (ISFM), which combines the use of organic and inorganic fertilizers has been promoted in sub-Saharan Africa since the 1990s as an effective strategy to combat soil fertility loss and increase agricultural output (Chivenge et al., 2010).

Ethiopian smallholder farmers rely heavily on teff (*Eragrostis tef* (Zucc.) Trotter) as a key source of income and a vital component in ensuring the country's food security (Hassen et al., 2018; Paff and Asseng, 2018). However, Ethiopia's teff grain production is lower (< 1.0 t ha^{-1}), mostly due to the limited fertility of the soil and smallholder farmers' inability to apply sufficient fertilizers (Haileselassie et al., 2011; Tesfahunegn, 2015). According to the reported literature, ISFM could enhance soil fertility and crop productivity including teff (Asaye et al., 2022; Bedada et al., 2014; Ejigu et al., 2021; Asmamaw et al., 2022; Agegnehu et al., 2016). However, ISFM often requires a significant input of organic residues (Hörner and Wollni, 2021). For instance, producing compost demands substantial biomass, which can frequently clash with other competing interests like livestock feed and cooking fuel (Doldt et al., 2023). In Ethiopia, around 85 % of crop residues are used as energy sources and fodder for livestock (Agegnehu and Amede, 2017), while most animal manure is also used for fuel, leaving only a small fraction of agricultural waste for soil improvement (Nigussie et al., 2015). The lack of sufficient organic material has been recognized as a major limitation in compost production (Asaye et al., 2022), highlighting the urgent need to find an alternative organic waste source for composting, such as aquatic weeds like water hyacinth (Singh and Kalamdhad, 2013; Islam et al., 2021).

Water hyacinth, originating from the Amazon basin in South America is among the top ten noxious global weeds (Villamagna and Murphy, 2010), invading Ethiopia's largest lake, Lake Tana, since 2011 (Anteneh et al., 2015; Van Oijstaeijen et al., 2020). Eradication of the weed is expensive, technically challenging, and frequently impossible, and the infestation in Lake Tana has progressed to the point where adaptation is unavoidable because of the prolific growth nature of the water hyacinth (Van Oijstaeijen et al., 2020). Physical, chemical, and biological methods have never been successful in controlling or managing the weed's rapid growth (Gajalakshmi et al., 2001). Moreover, in Lake Tana, with large-scale biowaste disposal problems and rapid weed growth, the primary regulating strategy of physical weed removal was unsuccessful (Gezie et al., 2018). As a method for controlling water hyacinth, utilizing its biomass could be a more effective strategy to curb the weed's proliferation (Gunnarsson and Petersen, 2007). Composting followed by soil application is considered one of the most cost-effective approaches for treating and disposing of water hyacinth (Singh and Kalamdhad, 2013; Gunnarsson and Petersen, 2007). Water hyacinth compost has a larger concentration of carbon (C) and other essential nutrients including nitrogen (N), phosphorus (P), and potassium (K), and applying it to the soil has a notable and beneficial effect on soil fertility (Balasubramanian et al., 2013; Mazumder et al., 2021). However, research on utilizing water hyacinth compost in field conditions remains underexplored (Osoro et al., 2014). Hence, further research is necessary to fully comprehend the effectiveness of using water hyacinth compost and its combined benefit with mineral fertilizers in enhancing soil fertility and crop performance.

In this study, we hypothesized that the massive biomass of water hyacinth from Lake Tana, Ethiopia, might be utilized to produce compost, which the soil could then be amended with the compost to enhance soil quality and teff crop yield when combined with mineral fertilizers. Removing the weed from the lake to protect the aquatic environment and improving soil fertility and crop yield would be the two key advantages of using water hyacinth for composting. Therefore, the study's objectives were to: (i) determine the phytotoxicity level of water hyacinth compost (ii) evaluate the impact of co-application of water hyacinth compost with mineral fertilizers on soil physicochemical properties, and (iii) assess the impact of combined use of water hyacinth compost with mineral fertilizers on teff growth and yield.

2. Materials and methods

2.1. *Water hyacinth compost preparation and analysis*

2.1.1. *Compost preparation*

Compost was prepared from November 2022 to February 2023 using water hyacinth (the main source) with other bulking agents (cow manure, rice straw, soil and ash). Cow manure was added to speed up the composting and enhance nutrient levels in the final compost product (Wan et al., 2012), while rice straw was added to adjust the C/N ratio and moisture level for efficient composting (Iqbal et al., 2010). Soil was utilized as a microbial source for organic matter decomposition (Nigussie et al., 2021), and adding ash plays a crucial role in regulating the compost pH levels and enhancing the liming effect of the final compost (Juárez et al., 2015; Kuba et al., 2008). Water hyacinth was collected before its flowering stage from Lake Tana, Northwestern Ethiopia (10°45′54.1′' N, 36°10′24.9′' E and 12°50′15.9′' N, 38°50′54.48′' E) at different infested areas of the lake. Cattle manure was collected from the cattle farm of the College of Agriculture and Environmental Sciences (CAES), Bahir Dar University, and rice straw was collected from farmers. Soil and ash were also collected from the CAES campus of Bahir Dar University. Before sun drying, fresh water hyacinth biomass was chopped into smaller pieces (2 - 3 cm). The drying was required to manage the moisture inside the compost mix. After sun drying the biomass for two weeks, the compost mix was made in a 50:30:10:10 ratio (dry weight basis) of water hyacinth, cow manure, rice straw, and a mix of soil and ash, respectively. The compost ingredients and ratios were based on Singh et al. (Singh et al., 2012), with some modifications of adding soil and ash. During mixing, water was sprinkled. The compost mix was then converted into a composting heap with a volume of 3 m^3 (1 m height, 1.5 m width, 2 m length). Plastic sheets covered the inner walls of the compost heap. A rice straw was laid at the base of the composting heap before converting the bulk compost mix. After constructing the compost hip, it was covered with grass to prevent moisture loss and allow air circulation. The compost moisture level was maintained at 60 % for better microbial activity (Gurusamy et al., 2021). The compost mix was turned once a month for better aeration and biomass degradation. The compost matured after four months of composting. Matured compost was air-dried, crushed, and screened using a 2-mm and 4-mm sieve for chemical analysis and land application, respectively.

2.1.2. *Compost phytotoxicity assessment*

Seed germination was conducted before use to test the phytotoxicity of compost. The seed germination test was done using cabbage (*Brassica oleracea*) and cress (*Lepidium sativum*) seeds which are sensitive to phytotoxicity (Luo et al., 2018). Compost (g) to distilled water (mL) aqueous solutions were prepared in different ratios (0.1:10 to 1:10).

After shaking for two hours in a horizontal shaker and letting the mix stand overnight, the mixture was filtered through a 0.45 μm membrane (Luo et al., 2018). The extract solution's pH and electrical conductivity (EC) are described in Table 1. Whatman No. 1 filter paper was laid on each petri dish, 10 mL of the aqueous extract was added, and 10 seeds of each test seeds were placed, and put in an incubator at a constant temperature of 25 °C for five days by sealing the petri dish using parafilm. After germination, the germination index (GI) was calculated by following the equations (Eq. (1) - 4) described in Luo et al. (Luo et al., 2018).

Table 1

The pH and EC values of the compost extract solution.

Parameters	Level of compost in the aqueous extract solution (g l^{-1})					
	0	20	40	60	80	100
pH	7.03 ± 0.026	7.79 ± 0.06	7.66 ± 0.04	7.64 ± 0.05	7.57 ± 0.03	7.49 ± 0.03
EC (dS m^{-1})	0.0034 ± 0.00	0.69 ± 0.005	1.24 ± 0.022	1.76 ± 0.02	2.27 ± 0.015	2.76 ± 0.04

EC: electrical conductivity; Values represent the mean ± SD ($n = 3$).

$$\textbf{Seed germination (SG)} = \frac{\textbf{\textit{Number of germinated seeds}}}{\textbf{\textit{Number of total seeds}}} * 100\ \% \tag{1}$$

$$\textbf{Relative seed germination (RSG)} = \frac{\textbf{\textit{Number of germinated seeds (sample)}}}{\textbf{\textit{Number of germinated seeds (control)}}} * 100\ \% \tag{2}$$

$$\textbf{Relative radicle growth (RRG)} = \frac{\textbf{\textit{Total radicle length of germinated seeds (sample)}}}{\textbf{\textit{Total radicle of germinated seeds (control)}}} * 100\ \% \tag{3}$$

$$\textbf{Germination index (GI)} = (\textbf{\textit{RSG}} * \textbf{\textit{RRG}}) * 100\ \% \tag{4}$$

2.1.3. Compost chemical analysis

To prepare for analysis, compost samples were taken from the bulk, air-dried, ground, and then passed through a 2 mm sieve. The pH and EC were measured from the extraction of a 1:10 w/v ratio of compost to distilled water (Singh et al., 2012). Organic C (OC) was determined by the wet digestion method (Wakley and Black, 1934). Total N (TN) was determined in the Kjeldhal digestion method (Bremner and Mulvaney, 1982). Available P (P_{av}) was analyzed by employing the Bray II method (Bray and Kurtz, 1954). A flame photometer was used to examine the exchangeable K (Ex. K) after it was extracted using 1 mol l^{-1} NH_4OAc (pH 7). The CEC was analyzed by applying the ammonium acetate (pH 7) method (Black, 1965). Table 2 displays the chemical characteristics of the compost prepared from water hyacinth.

Table 2

Chemical properties of compost developed from water hyacinth compost.

Compost parameter	Value	Compost parameter	Value
pH	7.58	C/N	8.85
EC (dS m^{-1})	2.69	P_{av} (mg kg^{-1})	276.5
OC (%)	8.29	CEC (cmol$_{(+)}$ kg^{-1})	50.9
TN (%)	0.94	Ex. K (cmol$_{(+)}$ kg^{-1})	9.96

Values are means of triplicate samples ($n = 3$); OC: organic carbon; C/N: carbon to nitrogen ratio; TN: total nitrogen; P_{av}: available phosphorus; CEC: cation exchange capacity; Ex. K: exchangeable potassium.

2.2. Field experiment

2.2.1. Study area description

The field experiment was conducted from June to October 2023, at the upper Blue Nile Basin's Koga irrigation scheme, south of Lake Tana, in a particular area called Ambomesk (Fig. 1). The experimental site was located at a latitude and longitude of 11°24′31′' N and 37°05′06′' E, respectively. The project site is located in the traditional agroecological zone of *Woina Dega* (1800 – 2400 m above sea level). With its primary peak occurring between June and September, the rainfall in the studied area has a predominately unimodal distribution. The average temperature during the field experiment was 18.9 °C. The long-term (2000 - 2022) mean monthly air temperature and rainfall are displayed in Fig. 2.

The dominant soil type in the area is Nitisol (Mekonnen, 2015). Before planting, three typical composite soil samples were collected at 0 to 20 cm depth from the experimental field. The core sampler method was used to calculate the soil's bulk density (Mihretie et al., 2021). The Boycous Hydrometer method was used to examine the soil texture (Page, 1982). The pH of the soil was measured from the suspension of a 1:2.5 of soil (g) to distilled water (mL) (Van Reeuwijk, 1995). Additional soil properties including OC, TN, P_{av}, Ex. K, and CEC were determined following the same procedure applied in the compost analysis described above in Section 2.1.3. According to Rowell (Rowell, 2014), soil samples were saturated with a 1 mol l^{-1} KCl solution, and the filtrate was titrated with 0.02 mol l^{-1} NaOH and 0.02 mol l^{-1} HCl to determine exchangeable acidity (Ex. A) and exchangeable Al (Ex. Al). The pre-planting soil physicochemical properties of the study site are presented in Table 3. The soil textural class is classified as heavy clay (> 50 % clay) (Hazelton and Murphy, 2016). The bulk density (1.29 g cm^{-3}) is lower than the critical limit (1.4 g cm^{-3}) for plant growth (Hazelton and Murphy, 2016). Based on the pH value (4.84), the soil was rated as strongly acidic with potential aluminum (Al^{3+}) ion concentration in the soil solution (Hazelton and Murphy, 2016). The organic C was low (Landon, 2014). However, the total N was at a medium level (Landon, 2014). The available P level was found in the lower range (Hazelton and Murphy, 2016). The CEC and exchangeable K were rated as medium and high, respectively (Roy et al., 2006).

2.2.2. Experimental design and treatment setup

The field experiment comprised a factorial combination of water hyacinth compost and inorganic fertilizers. The field experiment was carried out during the major growing season of 2023 under rainfed conditions. Four rates of water hyacinth compost (0, 8, 16, and 24 t ha^{-1}) and three rates of N/P_2O_5 fertilizers (0/0, 40/23, and 80/46 kg ha^{-1}) were arranged in a randomized complete block design in triplicates. For acidic soils, the recommended rate of N/P_2O_5 for teff cultivation is 80/46 kg ha^{-1} (Desta et al., 2023). The source of N and P_2O_5 fertilizers were urea and blended NPSB, respectively. Urea contains 46 % % N, whereas NPSB contains 18.9 %, 37.7 %, 6.95 %, and 0.1 % % N, P_2O_5, S, and B, respectively. A total of 36 plots each measuring 6 m^2 (2 m width, 3 m length) were prepared in three blocks. The field was plowed three times by using oxen-drawn implements before planting. To avoid treatment mix-ups, there were 1.5 and 1 m gaps between blocks and plots, respectively. Compost was manually added to the soil and well combined to the soil at a depth of 20 cm one month before sowing. The extension system's enhanced teff variety, *Quncho* (Dz-CR-387 RIL-355), the test crop, was sown at a seed rate of 25 kg ha^{-1} in June 2023. During

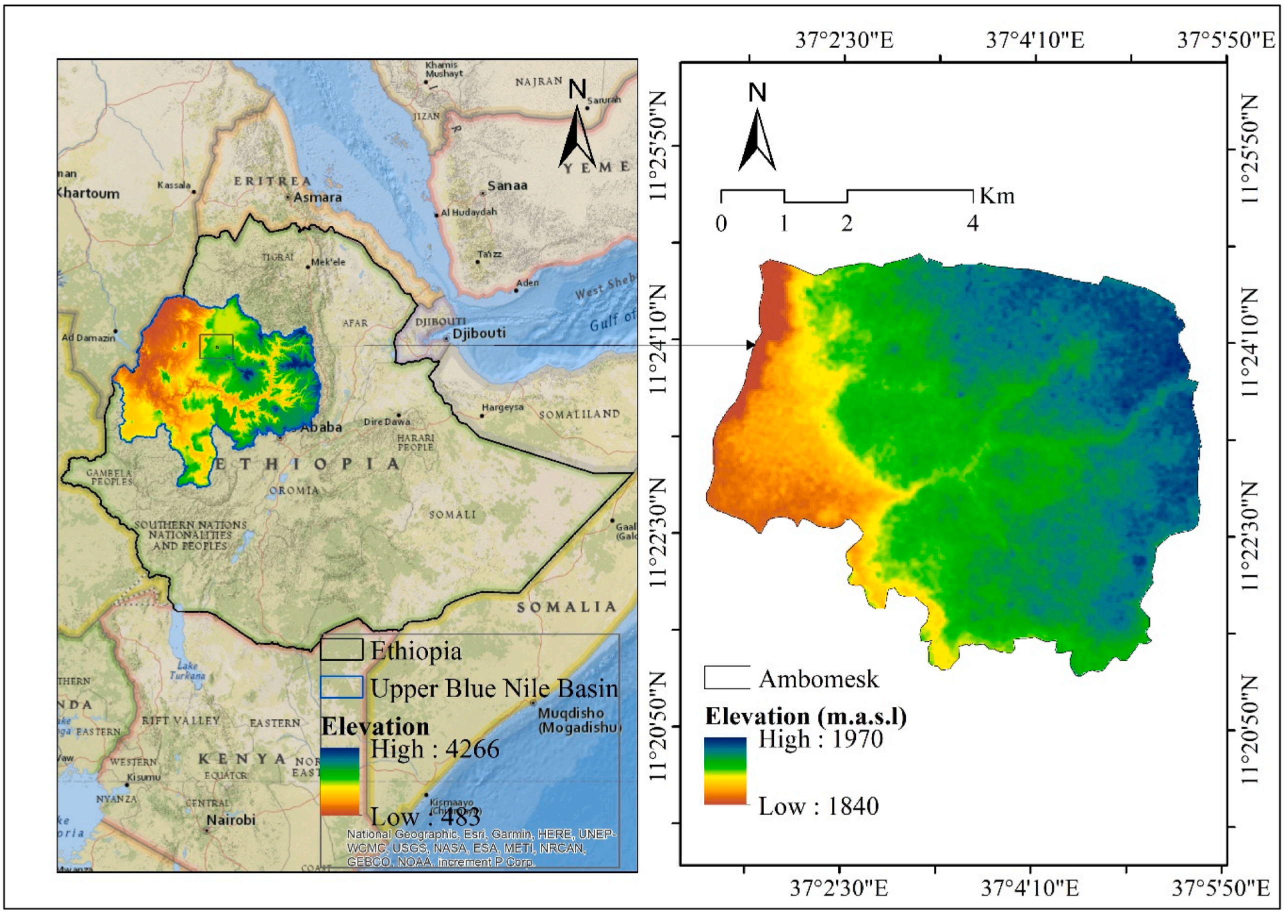

Fig. 1. Location map of the study area (Ambomesk) at the Koga Irrigation scheme, Upper Blue Nile Basin.

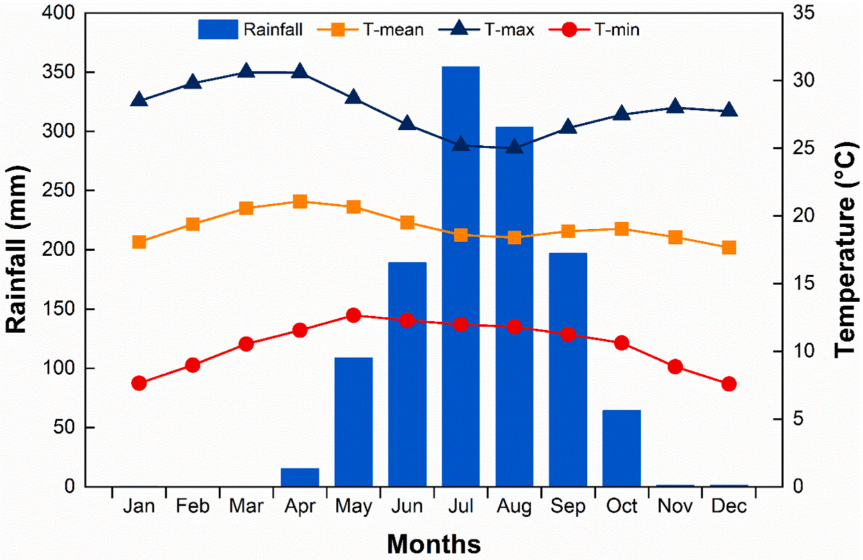

Fig. 2. The study area's long-term (2000 - 2022) average monthly rainfall and average (T-mean), maximum (T-max), and minimum (T-min) temperatures (Source: Merawi Meteorological Station, 2024).

sowing, the full dose of NPSB fertilizer was added while urea was added in split, the first part was applied during planting, and the second part was side-dressed when the crop was tillered. Every agronomic management technique used in teff growing was done manually following the extension's recommendations.

2.2.3. *Crop and soil data collection*

At physiological maturity, ten randomly chosen teff plants from the net plot were measured for average height from the soil line to the tip of the panicle with a measuring tape. On October 17, 2023 harvesting was undertaken when the crop reached physiological maturity. The total

Table 3
The physicochemical characteristics of the experimental soil before planting.

Soil parameter	Value	Soil parameter	Value
Clay (%)	54	TN (%)	0.21
Silt (%)	32	P_{av} (mg kg^{-1})	7.52
Sand (%)	14	CEC (cmol$_{(+)}$ kg^{-1})	23.3
Textural class	Clay	Ex. K (cmol$_{(+)}$ kg^{-1})	0.65
Bulk density (g cm^{-3})	1.29	Ex. Na (cmol$_{(+)}$ kg^{-1})	0.45
pH (H_2O)	4.84	Ex. A (cmol$_{(+)}$ kg^{-1})	3.17
OC (%)	1.88	Ex. Al (cmol$_{(+)}$ kg^{-1})	2.3

OC: organic carbon; TN: total nitrogen; P_{av}: available phosphorus; CEC: cation exchange capacity; Ex. K: Exchangeable potassium; Ex. Na: Exchangeable sodium; Ex. A: exchangeable acidity; Ex. Al: exchangeable aluminum.

biomass was calculated once the above-ground components of the crop were carefully harvested from the net plot and allowed to sun dry for a week. Before separating the grain, the total biomass was weighed and recorded using a sensitive balance. The grain yield was then measured using a sensitive balance by adjusting the grain moisture level to 12.5 % after the grain had been threshed, dried, and cleaned (Agegnehu et al., 2023). After weighing each yield parameter, the results were expressed per hectare (kg ha^{-1}) basis. The following formula (Eqn. (5)) was used to determine the grain harvest index.

$$\text{Harvest index (\%)} = (\text{Grain yield} / \text{Biomass yield}) * 100 \ (\tag{5}$$

After crop harvesting, using a soil auger, composite soil samples were collected at depths of 0 to 20 cm from each plot. By employing core samplers, samples of soil were collected from the middle of each plot for bulk density analysis. Composite soil samples were cleaned from plant materials, air-dried, crushed, and screened using a 2 mm sieve. The post-harvest soil samples were then examined for bulk density, pH, OC, TN, Pav, CEC, Ex. K, Ex. Ac, and Ex. Al followed the same procedures applied to analyze the pre-planting soil samples described in Section 2.2.1.

2.3. Data analysis

Descriptive statistics (mean ± SD) were applied to express the germination rate and germination index of cabbage and cress seeds to the phytotoxicity test per the various levels of compost in the aqueous solutions. Regarding the field data, the Shapiro-Wilk technique was initially used to verify the normal distribution of each dataset (Shapiro and Wilk, 1965). After the normality test, Fisher's least significant difference (LSD) test was applied to compare means after a two-way analysis of variance (ANOVA) was completed to detect treatment differences at the 5 % probability levels (Williams and Abdi, 2010). Pearson's correlation was conducted separately for teff yield parameters and soil parameters to examine the relationships within each set of variable and identify significant associations at a significance level of $P < 0.05$. A linear regression analysis was applied to determine the measured association between grain yield with compost and fertilizer levels, and soil properties. A generalized linear model was applied to the data through analysis using SAS 9.4 (SAS Institute, Cary, NC) statistical program.

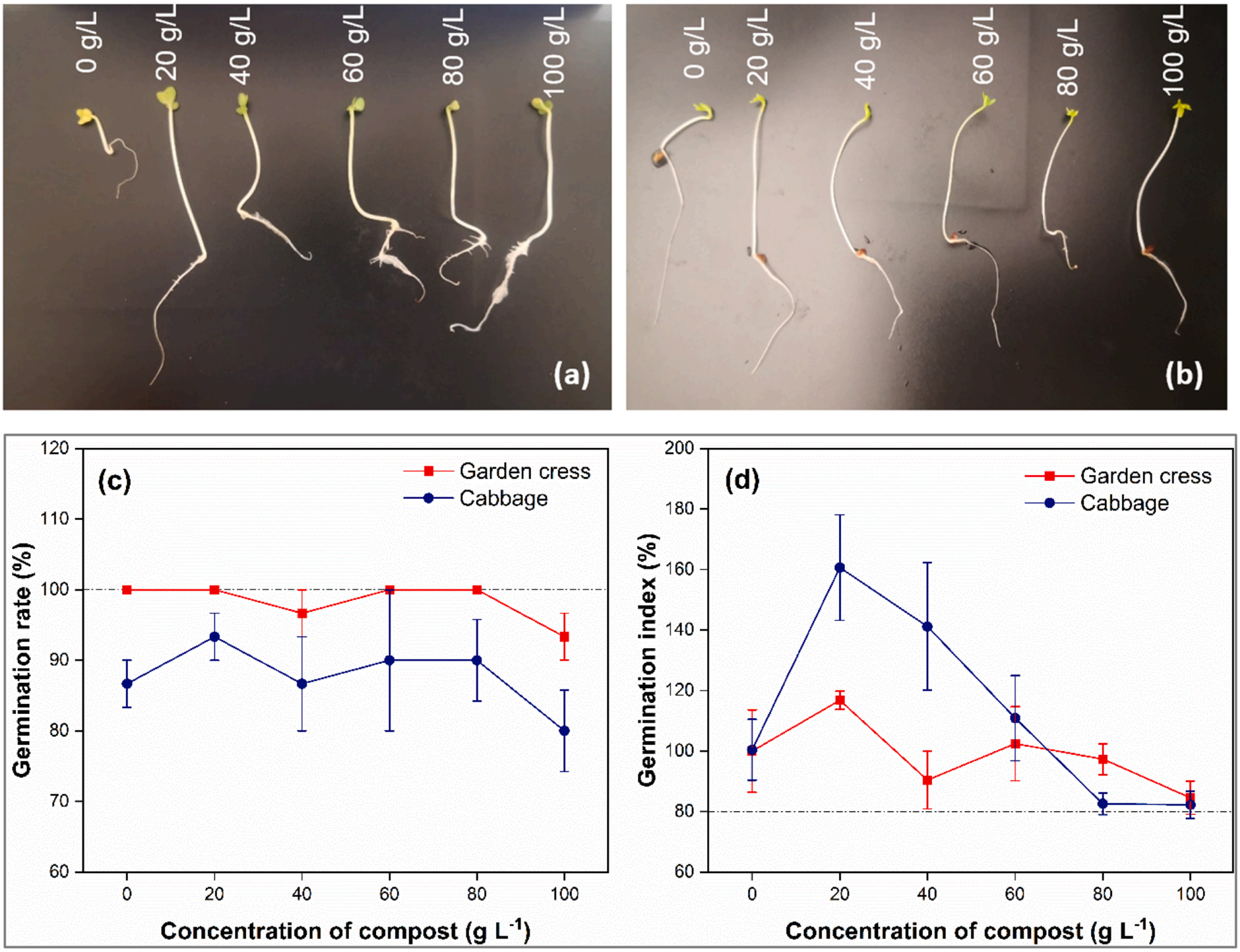

Fig. 3. Effect of different levels of compost concentration in the aqueous extract on seed germination of cabbage (a), and garden cress (b), percent rate of seed germination (c), and percent seed germination index (d). Horizontal broken lines represent the highest level of germination rate (c) and the lower threshold of germination index (d); Error bars represent ± standard deviations ($n = 3$).

Plotting the graphs was done using OriginPro software (OriginLab, USA).

3. Results

3.1. Compost phytotoxicity

The phytotoxicity (germination inhibition) test showed that water hyacinth compost extract did not inhibit the germination of cabbage and cress seeds (Fig. 3). As depicted in Fig. 3c & d, water hyacinth compost extract solution resulted in a germination rate (GR) of $\geq$ 80 % and > 90 % for cabbage and cress seeds, respectively. Similarly, the GI was greater than 80 % for both cabbage and cress seeds. The highest GI values of 161 % and 116 % were found at 20 g l^{-1} water hyacinth compost extract for cabbage and cress seeds, respectively.

3.2. Effect of water hyacinth compost and mineral fertilizer on soil properties and teff production

After harvesting, the tested soil parameters were markedly ($P < 0.05$) impacted by the addition of water hyacinth compost. The main effect of inorganic fertilizer application had only a significant ($P < 0.05$) impact on soil TN and P_{av}. However, there was no significant interaction effect on soil properties due to water hyacinth compost and mineral fertilizer (Table 4).

The mean values of soil parameters that are impacted by the main effects of applying mineral fertilizers and water hyacinth compost at varying rates are shown in Table 5. Soil bulk density was significantly reduced by 8.62 % and 10.3 %, respectively, when water hyacinth compost was applied at 16 and 24 t ha^{-1}. The soil's pH was increased by 0.32, 0.54, and 0.69 units with application of 8, 16, and 24 t ha^{-1} water hyacinth compost, respectively. Applying water hyacinth compost at an increasing level from 8 to 24 t ha^{-1} raised the soil OC by 10.3 % to 24.3 % compared to the non-amended treatment. The TN content was also improved by up to 28.6 % due to applying water hyacinth compost at different levels relative to the control. The P_{av} was significantly increased by applying water hyacinth compost at 8, 16, and 24 t ha^{-1} by 25.1 %, 45 %, and 80.2 %, respectively, compared to the control. The CEC was also improved by 20 % and 26.2 % over the control owing to applying water hyacinth compost at 16 and 24 t ha^{-1}, respectively. Relative to the control, the Ex. K level was increased by 40.0 %, 58.2 %, and 113 % because of the incorporation of water hyacinth compost at 8, 16, and 24 t ha^{-1}, respectively. In contrast, Ex. Ac and Ex. Al declined by 24.6 – 72.5 % and 25.5 – 78.6 %, respectively, due to the addition of water hyacinth compost at 8 - 24 t ha^{-1}. Applying different rates of mineral fertilizer increased soil TN significantly by 13 % over the unfertilized plots. Similarly, P_{av} was increased by 36.5 % and 56.3 % by application of mineral fertilizer at the half and full recommended rate, respectively, relative to non-fertilized treatment.

Table 4
An ANOVA in the rates of water hyacinth compost, mineral fertilizers, and their combination on nitisol properties.

Traits	Compost (C)	Fertilizer (F)	C × F	CV (%)	RMSE
Bulk density	<0.0001	0.973^{NS}	0.982^{NS}	4.23	0.05
pH	<0.0001	0.676^{NS}	0.345^{NS}	1.55	0.081
Organic C	<0.0001	0.967^{NS}	0.841^{NS}	3.95	0.083
Total N	<0.0001	0.0174	0.942^{NS}	7.77	0.019
Available P	<0.0001	<0.0001	0.989^{NS}	16.3	1.72
CEC	<0.0001	0.688^{NS}	0.958^{NS}	6.23	1.56
Exchangeable K	<0.0001	0.783^{NS}	0.773^{NS}	24.6	0.21
Exchangeable Acidity	<0.0001	0.052^{NS}	0.752^{NS}	27.6	0.58
Exchangeable Al	<0.0001	0.233NS	0.72^{NS}	31.3	0.45

CV: coefficient of variance; RMSE: root mean square error; CEC: cation exchange capacity; NS: non-significant.

3.3. Correlation between post-harvest soil properties

The Pearson's correlation coefficient indicated that the soil properties were significantly ($P < 0.05$, $P < 0.01$, $P < 0.001$) positively or negatively related with each other (Fig. 4). The soil bulk density was significantly negatively correlated with soil properties analyzed except Ex. A and Ex. Al ($r = 0.77, 0.81$, respectively). Soil pH had significantly strong positive correlations with soil OC ($r = 0.9$) and CEC ($r = 0.84$). However, soil pH was negatively strongly linked with Ex. A ($r =$ - 0.77) and Ex. Al ($r =$ - 0.81). The TN had a significant positive correlation with pH ($r = 0.0.75$), CEC ($r = 0.68$), and OC ($r = 0.57$). The P_{av} also exhibited a positive correlation with pH ($R^2 = 0.61$), OC ($R^2 = 0.67$), and CEC ($r = 0.56$). Additionally, P_{av} and TN were positively correlated ($r = 0.69$). Exchangeable potassium was positively associated with CEC ($r = 0.59$), pH ($r = 0.67$), and OC ($r = 0.69$). The exchangeable acidity and Ex. Al had a strong positive correlation ($r = 0.94$), however, they had a negative correlation with the other soil parameters.

3.4. Teff yield and yield components as affected by water hyacinth compost and mineral fertilizer

Co-application of water hyacinth compost with mineral fertilizer significantly impacted teff grain yield and total biomass. However, no significant interaction effect was found between fertilizer and water hyacinth compost on plant height and harvest index as Table 6 illustrates.

The results revealed that individual applications of water hyacinth compost and inorganic fertilizer resulted in significantly ($P < 0.05$) different grain and biomass yield of teff (Table 7). Increasing application rates of water hyacinth compost and fertilizer rate led to significant increases in grain and biomass yields, respectively. The main effects of compost indicated that applying water hyacinth compost at 8, 16, and 24 t ha^{-1} improved the grain yield by 13.5 %, 30.2 %, and 47.4 % over the zero-compost treated plot, respectively. Similarly, grain yield was impacted by the main effect of fertilizer application where the application of half and full fertilizer rates resulted in 121 % and 162 % increases, respectively, over the zero chemical fertilizer control plot. The plant height was also significantly ($P < 0.001$) affected by the separate application of water hyacinth compost and fertilizer. Applying water hyacinth compost at 16 and 24 t ha^{-1} increased teff plant height by 8.70 % and 10.3 %, respectively, relative to the control. Similarly, plant height was increased by 8.80 % and 11.8 % over the control with the addition of half and full rates of the recommended fertilizer. However, the grain harvest index was only substantially ($P < 0.05$) impacted by the mineral fertilizer application. With increasing the inorganic fertilizer level from none to the full recommended rate, the grain harvest index of teff dropped from 31.4 % to 22.2 %.

As shown in Fig. 5, teff grain yield and total biomass were significantly ($P < 0.05$) increased by the joint use of water hyacinth compost and chemical fertilizers. The largest grain yield (1826 kg ha^{-1}) was attained from 24 t ha^{-1} water hyacinth compost plus the full rate of the recommended fertilizer application. Conversely, the minimum grain yield (263 kg ha^{-1}) was found in the control treatment. Applying water hyacinth compost at 16 and 24 t ha^{-1} coupled with the maximum inorganic fertilizer rate raised the grain yield by 13.4 % and 28.6 %, respectively, over the sole fertilizer application at the highest level. Similarly, relative to the sole application of half of the recommended fertilizer rate, the grain yield was raised by 15.3 % and 21.6 % by applying 16 and 24 t ha^{-1} water hyacinth compost combined with half of the recommended mineral fertilizer rate. Similarly, the highest teff total biomass (8020 kg ha^{-1}) was recorded by coapplying 24 t ha^{-1} of compost with the highest level of mineral fertilizer. The total biomass obtained at the application of 16 and 24 t ha^{-1} water hyacinth compost plus the full recommended rate of fertilizer increased the total biomass by 12.6 % and 22.1 % over the full recommended fertilizer rate applied without compost. Moreover, there were no significant grain and biomass yield

Table 5
Main effects of water hyacinth compost and mineral fertilizer on mean soil properties.

Compost (t ha^{-1})	BD (g cm^{-3})	pH	OC (%)	TN (%)	Pav (mg kg^{-1})	CEC (cmol$_{(+)}$ kg^{-1})	Ex. K	Ex. A	Ex. Al
0	1.26b	4.81d	1.85d	0.21c	7.66c	22.1a	0.55c	3.38a	2.43a
8	1.21b	5.13c	2.04c	0.24b	9.58b	23.7a	0.77b	2.55b	1.81b
16	1.16a	5.35b	2.17b	0.26ab	11.1b	26.5b	0.88b	1.59c	0.96c
24	1.13a	5.5a	2.3a	0.27a	13.8a	27.9c	1.17a	0.93d	0.52d
LSD $_{(0.05)}$	0.05	0.078	0.08	0.019	1.67	1.52	0.2	0.57	0.44
N/P$_2$O$_5$ (kg ha^{-1})									
0	1.19	5.21	2.09	0.23b	8.06c	25.0	0.83	1.76	1.24
40/23	1.19	5.21	2.09	0.25ab	11b	24.8	0.87	2.27	1.5
80/46	1.18	5.18	2.1	0.26a	12.6a	25.4	0.82	2.31	1.54
LSD $_{(0.05)}$	0.042	0.068	0.07	0.016	1.45	1.31	0.174	0.5	0.38

BD: bulk density; OC: organic carbon; TN: total nitrogen; Pav: available phosphorus; CEC: cation exchange capacity; Ex. K: exchangeable potassium; Ex. A: exchangeable acidity; Ex. Al: exchangeable aluminum.

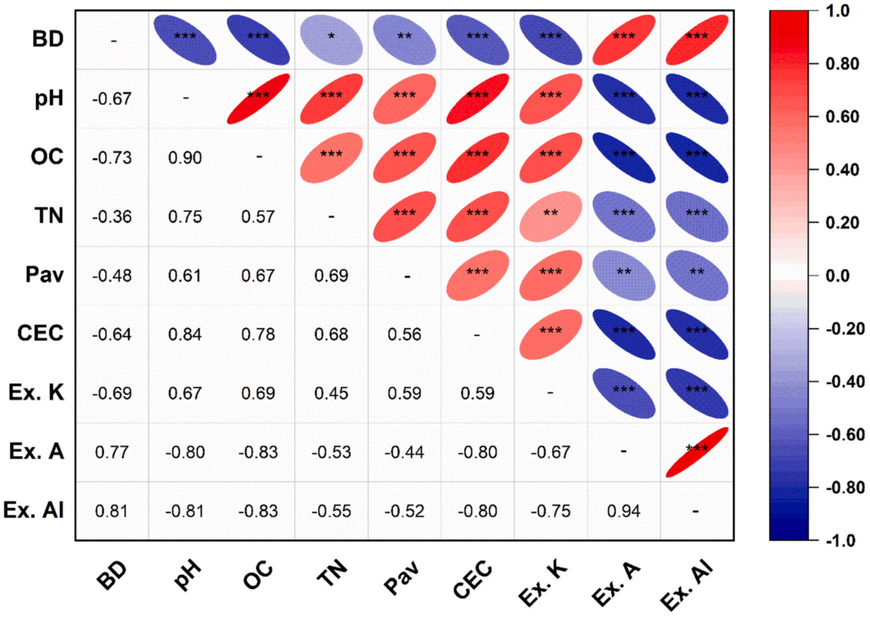

Fig. 4. Pearson correlations among soil properties; BD: bulk density; OC: organic carbon; TN: total nitrogen; P$_{av}$: available phosphorus; CEC: cation exchange capacity; Ex. K: exchangeable potassium; Ex. A: exchangeable acidity; Ex. Al: exchangeable aluminum. *, **, ***, significant values at $P < 0.05$, $P < 0.01$, $P < 0.001$, respectively.

Table 6
Significance of the effects of different rates of water hyacinth compost, mineral fertilizers, and their interaction on teff productivity.

Traits	Compost (C)	Fertilizer (F)	C × F	CV (%)	RMSE
Grain yield	<0.0001	<0.0001	0.0021	7.13	84.8
Biomass yield	<0.0001	<0.0001	0.0298	6.75	325.1
Plant height	0.0013	0.0093	0.54^{NS}	6.71	7.27
Harvest index	<0.0001	0.455^{NS}	0.061^{NS}	11.2	3.0

CV: coefficient of variance; RMSE: root mean square error; CEC: cation exchange capacity; NS: non-significant.

differences between applying half of the recommended fertilizer with 24 t ha^{-1} compost and only the maximum rate of inorganic fertilizer application. The tallest (117.7 cm) and shortest (91.2 cm) teff plant heights were observed from the addition of 24 t ha^{-1} plus the full rate of mineral fertilizer and the control treatments, respectively. Likewise, despite being non-significant due to the interaction effect of applying compost with fertilizer, the harvest index showed a declining trend with the rise in compost and fertilizer applications.

Table 7
The mean values of the main effects of water hyacinth compost and mineral fertilizer management strategies on teff yield and growth parameters.

Compost (t ha^{-1})	Plant height (cm)	Grain yield (kg ha^{-1})	Total biomass (kg ha^{-1})	Harvest index (%)
0	103.1b	969d	3790d	27.8
8	104.6b	1100c	4433c	26.5
16	112.1a	1262b	5078b	26.7
24	113.7a	1428a	5970a	25.5
LSD $_{(0.05)}$	7.07	82.5	316.3	2.91
N/ P$_2$O$_5$ (Kg ha^{-1})				
0/0	101.4c	613c	1932c	31.4a
40/23	110.3b	1354b	5279b	26.3b
80/46	113.4a	1603a	7243a	22.2c
LSD $_{(0.05)}$	6.71	71.5	273.9	2.52

Mean values sharing the same letters within the same column are not significantly different at $P < 0.05$.

3.5. Relationship between teff grain yield and other yield parameters

According to the linear regression analysis results, the grain and biomass yield increased with increased levels of mineral fertilizer and water hyacinth compost as a main function (Fig. 6). Compared to the

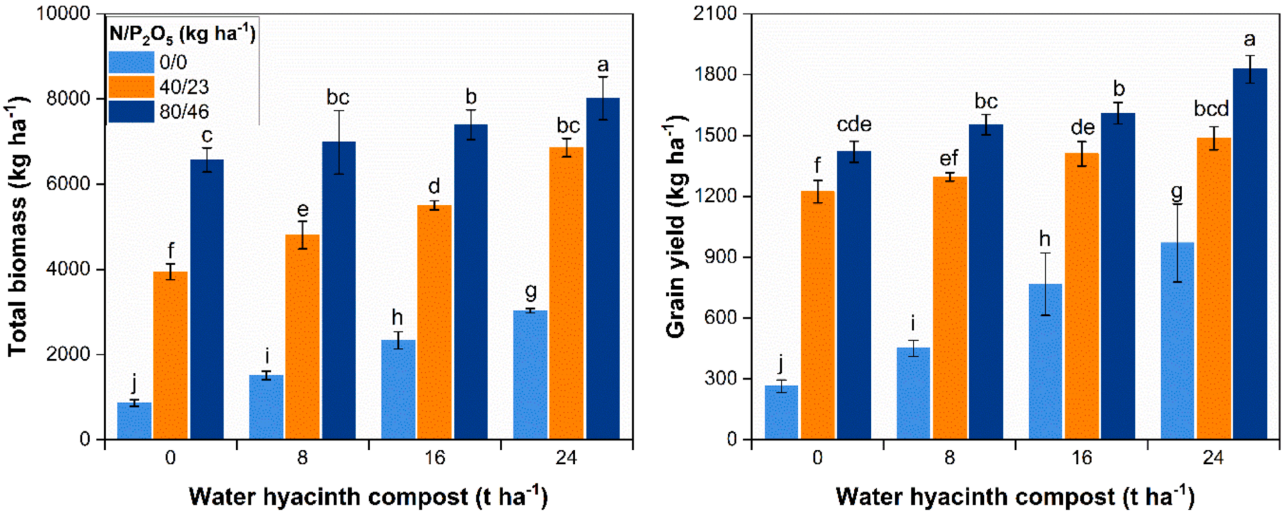

Fig. 5. The interaction effect of water hyacinth compost and mineral fertilizer on total biomass and grain yield of teff.

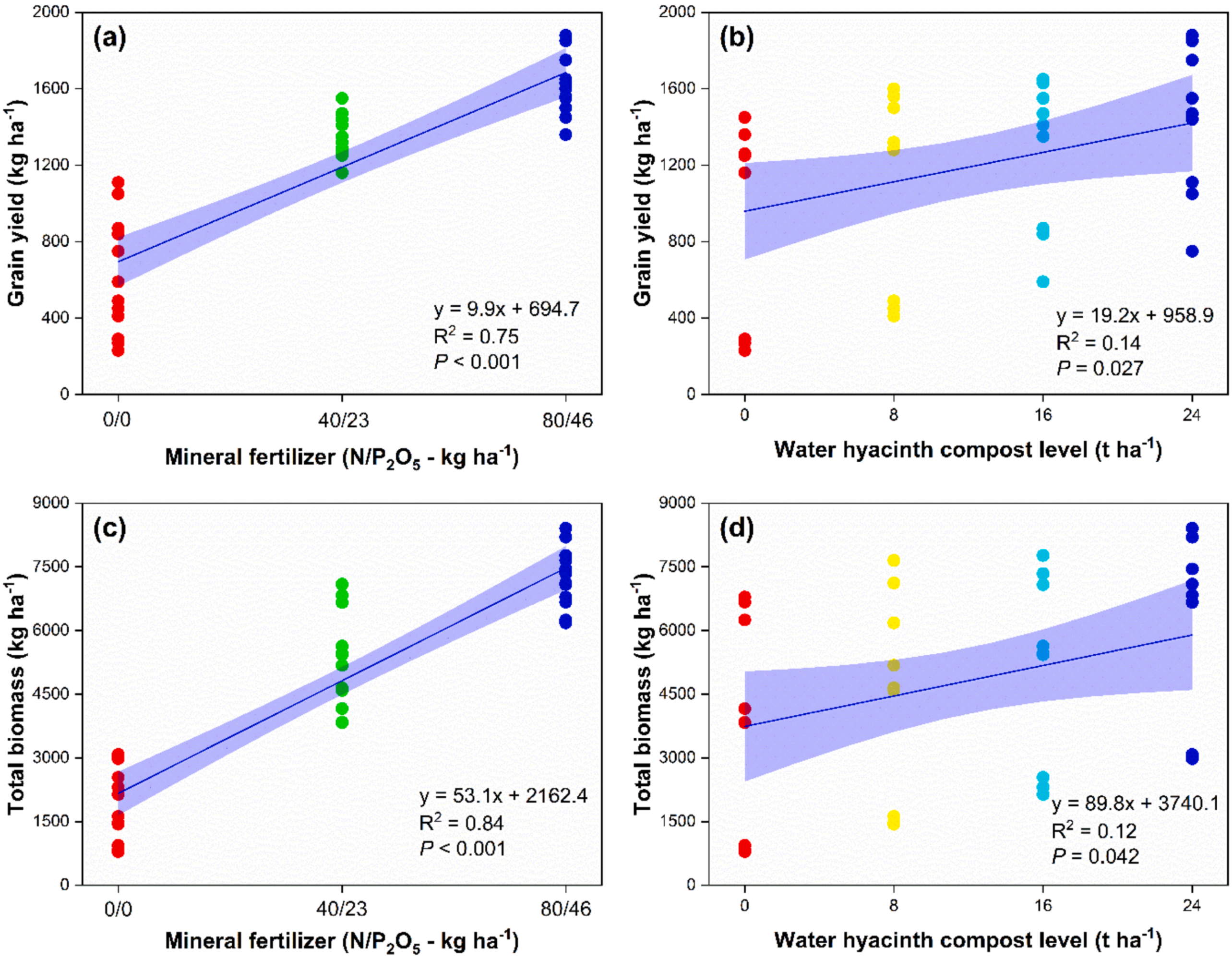

Fig. 6. A linear regression fitting between grain yield with mineral fertilizer level (a), and water hyacinth compost level (b), and biomass yield with mineral fertilizer level (c), and water hyacinth compost level (d) of teff crop.

level of water hyacinth compost, the level of mineral fertilizer had a strong positive relation with grain yield ($R^2 = 0.75$, $P < 0.001$) and total biomass ($R^2 = 0.84$, $P < 0.001$). The compost level was also positively related to grain yield ($R^2 = 0.14$, $P = 0.027$) and total biomass ($R^2 = 0.12$, $P = 0.042$).

Pearson's correlation analysis showed that the grain yield was significantly and positively correlated ($r = 0.95$, $P < 0.001$) with the total biomass (Table 8). Similarly, a positive and significant correlation ($r = 0.72$, $P < 0.001$) occurred between the grain yield and the plant height. However, the grain yield was significantly and negatively

Table 8
Pearson's correlation among teff yield parameters.

Parameters	Grain yield	Total biomass	Plant height	Harvest index
Grain yield	–	0.95***	0.72***	−0.62***
Total biomass	0.95***	–	0.67***	−0.80***
Plant height	0.72***	0.67***	–	−0.39*
Harvest index	−0.62***	−0.80***	−0.39*	–

* and *** denote significant correlation at the 0.05 and 0.001 levels, respectively.

associated ($r = -0.62$, $P < 0.001$) with the harvest index of teff. The total biomass of teff was also significantly and positively ($r = 0.67$, $P < 0.001$) linked to the average height of the plant, however, the correlation with the grain harvest index was significantly negative ($r = -0.80$, $P < 0.001$). The plant height was also significantly and negatively related ($r = -0.39$, $P = 0.019$) to the grain harvest index.

3.6. *Relationships between teff grain yield and soil properties*

The regression analysis fitting showed that the highest significant ($P < 0.001$) fitting ($R^2 = 0.6$) was found from grain yield with P_{av}, followed by the second highest significant ($p < 0.001$) fitting ($R^2 = 0.31$) of grain yield with soil TN (Fig. 7). The grain yield was also significantly ($P = 0.041$) correlated ($R^2 = 0.12$) with the OC content of the soil. Likewise, the grain yield was significantly ($P = 0.038$) linked with the soil's CEC ($R^2 = 0.12$). The association of grain yield with Ex. K was positive, but not significant. However, the bulk density of the soil and Ex. Al demonstrated a negative but insignificant relationship with grain yield. The regression analysis designates that improving soil properties including pH, TN, P_{av}, OC, and CEC, and reducing exchangeable acidity and Al^{3+}, can increase grain yield.

4. Discussion

4.1. *Compost phytotoxicity*

Germination index (GI) is a widely used, accurate, and sensitive biological metric for evaluating compost maturity and phytotoxicity (Zhan et al., 2021). The germination test conducted using *Brassica oleracea* and *Lepidium sativum* demonstrated that compost produced from water hyacinth did not pose any phytotoxic effects on seed germination, as evidenced by GI value exceeding 80 %. High GI values could be due to the complete maturity of the compost and the low level of heavy metal pollution in Lake Tana, where the water hyacinth was collected. A GI value greater than 80 % is considered the low benchmark for a compost devoid of phytotoxicity (Cesaro et al., 2015). Moreover, GI greater than 50 % also signifies high-quality compost in terms of both maturity and phytotoxicity (Zucconi et al., 1981). In agreement with this

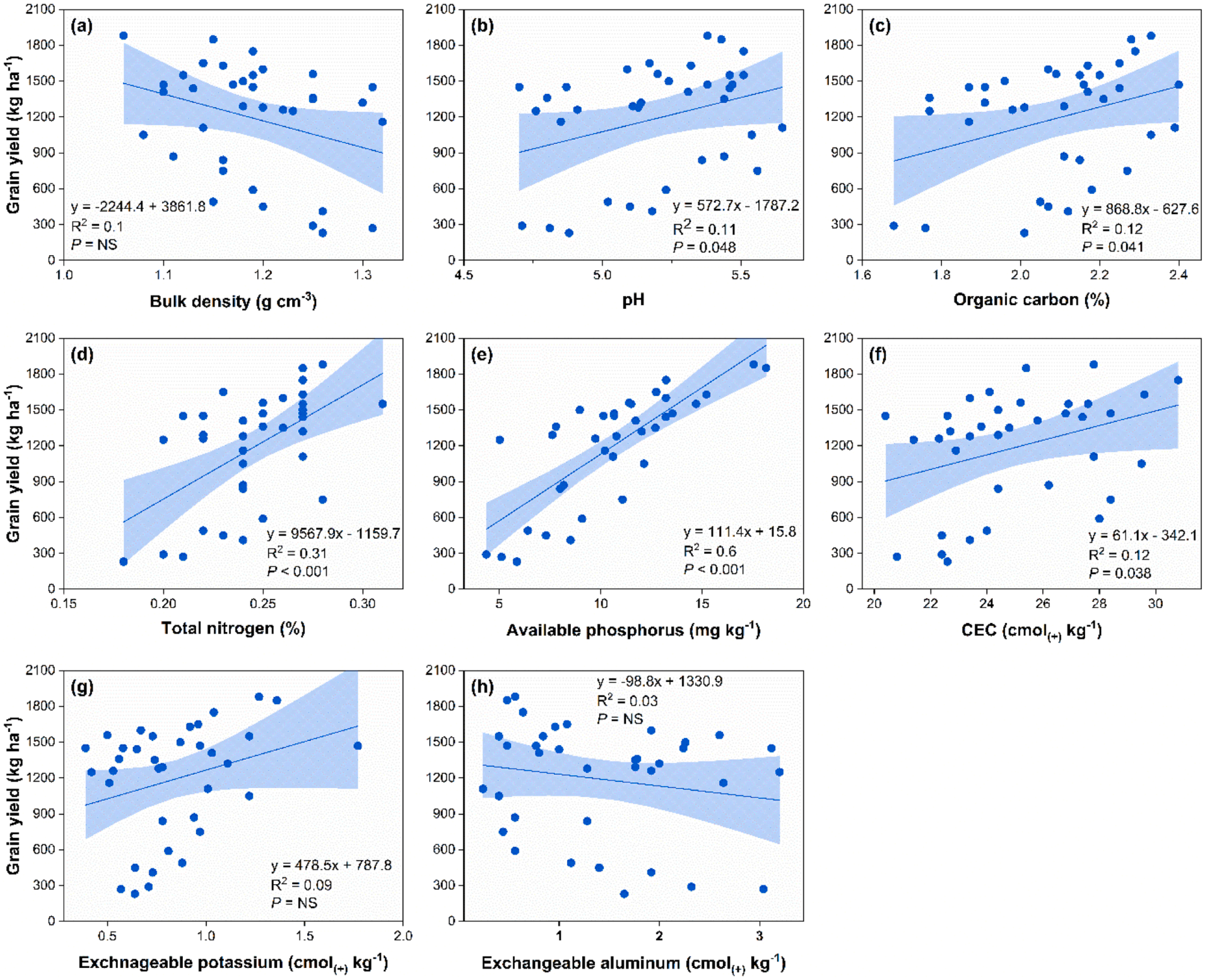

Fig. 7. Relationships between grain yield with soil bulk density (a), pH (b), organic carbon (c), total nitrogen (d), available phosphorus (e), cation exchange capacity (CEC) (f), exchangeable potassium (g), and exchangeable aluminum (h). NS: non-significant.

study, GI indices recorded for compost derived from water hyacinth sourced from contaminated water sources ranged from 53.9 – 184 % and 47.1 – 135 % for L. *esculentum* and *B. oleracea*, respectively (Mazumder et al., 2020). Fully matured compost can be utilized for soil use as an organic supplement to enhance both plant growth and soil fertility (Luo et al., 2018). Hence, applying compost derived from water hyacinth collected from fresh waters can be considered safe for soil conditioning and crop cultivation.

4.2. Soil improvement due to water hyacinth compost and mineral fertilizer

The combination of water hyacinth compost and mineral fertilizer had no interaction effect on soil properties. Nevertheless, each amendment significantly affected soil properties (Table 4). Only soil TN and P_{av} were substantially affected by adding mineral fertilizers at varying levels. This could be due to the direct nutrient input from the mineral fertilizers. However, applying water hyacinth compost significantly affected all soil parameters tested. Applying compost resulted in a significant reduction in soil bulk density. According to Ahmad et al. (Ahmad et al., 2021) compost provides several advantages to soil, including decreasing soil bulk density and enhancing its ability to retain water. In line with the present study, the addition of compost at 10 t ha^{-1} in barley-cultivated soil reduced the bulk density by 8.3 % (Agegnehu et al., 2016). Moreover, the use of compost at a similar rate decreased soil bulk density by 11.4 % (Ejigu et al., 2021). A large soil bulk density reduction (24.8 %) was reported from land supplied with compost in every growing season for three consecutive years relative to the control (Chen et al., 2022).

Water hyacinth compost significantly raised soil pH. This could be due to the alkaline nature of water hyacinth compost and its high CEC (Table 3). Organic fertilizers like compost better mitigating soil acidification than applying chemical fertilizers alone (Dai et al., 2021). In agreement with our result, compost applied at 10 t ha^{-1} in teff cultivated land raised the soil pH by 0.67 units (11.9 %) (Ejigu et al., 2022). Bedada et al. (Bedada et al., 2014) noted that following six years of continuous compost application the topsoil pH in the inorganic fertilizer-treated soil was lesser than the compost and compost plus mineral fertilizer treatments by 0.39 and 0.2 units, respectively. After a decade, the incorporation of compost increased the soil pH by 0.36 units compared to the untreated control, while only chemical fertilizer treatment reduced the pH by 0.91 units (Dai et al., 2021). Consequently, one way to ameliorate agricultural soils acidity would be by applying water hyacinth compost.

Applying water hyacinth compost significantly increased the soil's OC content. The OC could be raised by the added organic matter from the compost. Consistent with our result, after six years of compost fertilization the soil OC increased by 12.1 % (Bedada et al., 2014). Under teff cultivated land, the OC content of the soil was found higher in compost-treated soil than in mineral fertilizer-treated by 15.8 % (Ejigu et al., 2022). In line with our result, the successive application of compost for 12 growing seasons at 15, 30, and 45 t ha^{-1} elevated the soil organic matter by 34.2 %, 78.6 %, and 110 %, respectively, over the control (Chen et al., 2022). The results indicate that applying water hyacinth compost will have a beneficial effect on improving soil OC and overall soil health and fertility.

Composted water hyacinth significantly increased the soil's P_{av} and TN contents. Applying water hyacinth compost and its subsequent breakdown of organic matter likely increased soil nutrition by supplying N and P. The increase in the available P could also be due to the rise in soil's pH and the release of P previously fixed by oxides of Al and sesquioxide, as demonstrated by a significant correlation found between soil pH and P_{av} (Fig. 4). Research indicates that compost reduces phosphorus fixation and sorption in acidic soils, improving phosphorus uptake, crop yield, and lowering soil acidity and aluminum toxicity (Agegnehu et al., 2016). Additionally, the correlation analysis revealed that TN and P_{av} were significantly correlated with the OC, a key fraction of the organic matter. In Lake Tana, it was reported that the water surface covered with water hyacinth was rich in N and P contents due to the continuous supply of nutrients from the surrounding farmlands through erosion (Dersseh et al., 2022). According to Gunnarsson and Petersen (Gunnarsson and Petersen, 2007), with a C/N ratio of 15 and N content of up to 3.2 % of the dry matter, water hyacinths are a rich source of N. Consistent with our findings, applying water hyacinth compost greatly raised the TN and P_{av} contents of the tested soil (Mazumder et al., 2021). This indicates that water hyacinth compost could be a potential nutrient source to increase agricultural yield and soil fertility.

The soil's CEC was substantially improved owing to the high CEC and increased level of water hyacinth compost application. As indicated in Fig 4, CEC was found strongly correlated with the soil OC content, which could improve soil CEC. In line with our result, the application of compost at 10 t ha^{-1} in teff cultivated land enhanced the soil CEC by 9.35 % and 5.46 % compared to the sole fertilizer and control treatments, respectively (Ejigu et al., 2022). Similarly, applying compost at 10 t ha^{-1} raised the CEC of two different soil types by more than 20 % (Agegnehu et al., 2016). The improvement in CEC enhances soil fertility by increasing nutrient availability, as it helps the soil retain nutrients, preventing it from being washed away through leaching (Xu et al., 2012). Applying water hyacinth compost also raised the K content of the treated soils. Raised soil pH, CEC, and K supply due to the addition of compost might be the reason behind improved K levels in the soil. According to Taiwo et al. (Taiwo et al., 2018), increasing biological activity in soils led to an increase in the availability of K. Compost application significantly increases biodiversity and soil microbial activity, speeding up nutrient cycling in the soil (Morillo et al., 2009).

By adding water hyacinth compost, the amount of Ex. A and Ex. Al in the soil were greatly decreased, and the effect grew in parallel with the compost addition rate. This might be ascribed to the improved pH and CEC owing to the addition of alkaline water hyacinth compost. The correlation analysis also showed that the soils Ex. A and Ex. Al were significantly and negatively correlated with pH (Fig. 4), indicating the positive effect of the water hyacinth compost in reducing Ex. Al through bocking the exchangeable sites. In agreement with our result, applying compost at the level of 3 and 6 t ha^{-1} minimized soils' Ex. A by 8.3 % and 27.6 %, respectively (Ejigu et al., 2023). In addition, with the same rates of compost addition Ex. Al declined by 15.5 % and 43.0 %, respectively, relative to the control (Ejigu et al., 2023). Likewise, Ex. A and Ex. Al were diminished by 44.0 % and 37.5 %, respectively, over the control after 10 years of fertilization with compost (Dai et al., 2021). Based on this, soil acidity can be ameliorated by applying water hyacinth compost.

4.3. Crop response to combined water hyacinth compost and mineral fertilizer application

The joint use of water hyacinth compost alongside inorganic fertilizers enhanced the grain and biomass yield of teff grown in Nitisols, characterized by low soil fertility and high acidity (Table 2). Among the main factors reportedly restraining the yield of teff was poor soil fertility (Haileselassie et al., 2011; Tesfahunegn, 2015; Mihretie et al., 2022). In this study, the increased teff grain and biomass yield might be due to enhanced soil physicochemical properties and nutrient availability, which could be attributed to the coapplication of water hyacinth compost and mineral fertilizer. The regression analysis also demonstrated that the grain and total biomass yield of teff was enhanced by raising the amount of mineral fertilizers and water hyacinth compost (Fig. 6). In addition, the regression analysis also revealed significant correlations between grain yield and various soil properties (Fig. 7). An increase in crop yield was more pronounced when organic amendments were applied together with mineral fertilizers, as opposed to adding either resource individually (Chivenge et al., 2010). In agreement with the present study, several studies indicated that teff production was improved with the joint use of organic and inorganic fertilizers (Ejigu et al., 2022; Agegnehu et al., 2014; Girma and Gebreyes, 2017; Habte et al., 2018; Hunegnaw et al., 2021). It has been noted that P and N are the primary nutrients that restrict teff growth in dryland production systems (Girma et al., 2012). Even in acidic soils with ideal fertilizer application rates, teff yields were extremely low (Agegnehu et al., 2023). Accordingly, the N use efficiency is increased and potential N losses are decreased when organic and inorganic amendments are applied jointly (Agegnehu et al., 2016; Zhang et al., 2016). Moreover, the integrated utilization of compost and mineral fertilizers enhances critical soil properties such as soil structure, pH, CEC, and biological diversity, facilitating the effective availability of nutrients and absorption by crops (Oyetunji et al., 2022). Additionally, by reducing the amount of exchangeable Al^{3+}, pH increase helps to reduce the Al toxicity (Domínguez et al., 2019). However, the combined use of water hyacinth compost with mineral fertilizers on the harvest index was not significant and showed a declining trend with increasing application rate of compost and fertilizer. The harvest index was only impacted due to the application of mineral fertilizers at varying levels. Moreover, the grain yield was negatively correlated with the harvest index. This could be caused by excessive growth of the teff total biomass that led to lodging of the crop consequently leading to a grain loss. Every year in Ethiopia, lodging happens within teff fields regardless of the weather, resulting in yield losses of approximately 25 % (Tefera and Ketema, 2001), which can escalate even over 50 % in severe instances (Bennetzen et al., 2009). The lodging of cereal crops is greatly impacted by the optimization of N levels and seed rate (Wu et al., 2019; Zhang et al., 2014). Consequently, one way to increase crop production could be applying compost made from water hyacinth along with the ideal rate of mineral fertilizers.

5. Conclusion

Our study highlights the significant benefits of incorporating compost derived from water hyacinth alongside mineral fertilizers, both in improving soil quality and enhancing teff productivity. Notably, the absence of any phytotoxic effects from water hyacinth compost indicates its safe use for crop production and soil health management. Our findings suggest that applying water hyacinth compost and mineral fertilizers in conjunction produces better soil characteristics and crop yield outcomes than their sole application. Specifically, the integration of 24 t ha^{-1} water hyacinth compost with the maximum recommended rate of mineral fertilizers led to the highest teff grain and biomass yield. Moreover, the grain yield attained by applying 24 t ha^{-1} water hyacinth compost with half of the recommended fertilizer rate was comparable with the sole application of the full recommended rate of inorganic fertilizer. Applying water hyacinth compost showed the potential of replacing 50 % of the mineral fertilizer. This indicates that by improving soil fertility and enhancing agricultural and environmental sustainability, the long-term combined use of organic and inorganic sources may appreciably reduce the need for inorganic nutrients. Furthermore, while the study was confined to a one-year field experiment, it represents a vital step towards water hyacinth management through composting and emphasizes the positive impact of integrating water hyacinth compost with mineral fertilizers. Hence, composting water hyacinth and its soil application emerge as a promising strategy for weed control and organic waste management. Future investigations should prioritize field experiments over years, locations, and soil types to further elucidate the effects of water hyacinth compost application on soil properties and crop productivity.

Funding

This study was funded by MEXT/Japan-funded Plankton Ecoengineering for Environmental and Economic Transformations project as well as the Japan Science and Technology Agency/JST and Japan International Cooperation Agency/JICA-funded Project for Eco-Engineering for Agricultural Revitalization Toward Improvement of Human Nutrition/ EARTH: Water Hyacinth to Energy and Agricultural Crops through the Japan Science and Technology Research Partnership for Sustainable Development/SATREPS (grant number- JPMPSA2005).

CRediT authorship contribution statement

Ashenafei Gezahegn: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yihenew G. Selassie:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Getachew Agegnehu:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Solomon Addisu:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Fekremariam Asargew Mihretie:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Yudai Kohira:** Writing – review & editing, Methodology, Conceptualization. **Mekuanint Lewoyehu:** Writing – review & editing, Methodology, Conceptualization. **Shinjiro Sato:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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