



# Integrating rainwater harvesting and organic soil amendment to enhance crop yield and soil nutrients in agroforestry

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## Abstract

More than 90% of rainfed croplands in Sub-Saharan Africa (SSA) are severely affected by highly intermittent rainfall and frequent drought limiting crop productivity in the region. Besides, 27.1% of the population in SSA are currently food insecure and this is likely to increase with the current rapid population growth in the region. Soil erosion and water scarcity remain to be the core problem affecting agricultural productivity of smallholder farming. In the current study, we analysed rainwater harvesting assisted small-scale agroforestry system in order to mitigate both soil erosion and water scarcity issues simultaneously. The system included in-situ rainwater harvesting, soil organic amendment (raw poultry litter, poultry litter biochar, wood ash) and an agroforestry system (AFS) containing maize, barley- *Eucalyptus globulus* all intercropped in a holistic approach. The effect was evaluated on selected soil parameters and crop yield in a field experiment on a completely randomized design. The treatments were poultry litter (PWAFS), poultry litter biochar (BWAFS) wood ash (AWAFS) with supplementary irrigation (WAFS) and agroforestry system AFS (control). The first three treatments contained poultry litter, poultry litter biochar and wood ash along with rainwater harvesting respectively while the fourth treatment contained only rainwater harvesting. Besides, a control plot-AFS was assigned with neither rainwater harvesting nor soil organic resources. The result indicated that BWAFS increased the pH by 19.4% followed by AWAFS and PWAFS (9%). Maximum and minimum SOM (2.26%, 1.21%) were observed under BWAFS and the control (AFS) respectively. BWAFS significantly increased Av.P by 78.1% while WAFS increased by 40% compared to the control. Similarly, BWAFS and PWAFS had significant effect on maize yield with increase by 74% and 36% respectively. The study concluded that integrating rainwater harvesting and soil amendment with agroforestry systems can enhance crop yield and soil nutrient levels. Therefore, such agricultural practices should be adopted by smallholder farmers in areas with limited water and nutrients levels.

**Keywords** Regenerative Agriculture · Poultry Litter · Biochar · Rain Water Harvesting · Supplementary Irrigation · Wood Ash

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Extended author information available on the last page of the article

## 1 Introduction

A significant portion of the population (27.1%) in Sub-Saharan Africa (SSA) is currently experiencing food insecurity (Wudil et al., 2022). This issue is exacerbated by the severe impact of intermittent rainfall, which hampers crop productivity in over 90% of the region's rainfed croplands (Kim et al., 2021). Moreover, the problem of food insecurity is expected to worsen due to increasing population pressure in SSA (Tantoh, 2023). The erratic nature of rainfall has caused longer dry spells (Rosa et al., 2020) which in turn resulted in excessive moisture stress and massive yield losses (Falkenmark, 2020). Regenerative agricultural practices such as Agroforestry can have significant potential in creating a climate resilient agriculture, maintaining soil fertility and providing diverse ecosystem services (Dev et al., 2018). The integration of trees with in farming systems provides a continuous organic matter input to the soil via their leaf litter and root turnovers. This enhances soils physical, chemical and biological characteristics (Fahad et al., 2022). According to Silva et al. (2022), agroforestry systems indicated a short term effect on soil quality indicators including increased pH and potassium levels compared to pastures and forests in southern Brazil. In designing agroforestry systems, it is desirable to select fast growing multipurpose trees that can simultaneously increase soil organic matter and provide high market values (Mengistu et al., 2022). A recent study on eucalyptus based agroforestry system in India increased both soil organic carbon and total nitrogen than mono cropping (Singh et al., 2021). Similarly, a study in semi-arid area in India reported an increase in barley yield, soil nitrogen, phosphorus and potassium under eucalyptus based agroforestry systems (Bhardwaj et al., 2017).

During intercropping, trees may outcompete for resources such as water and nutrients due to their extensive root and high biomass production rates. Incorporating rainwater harvesting techniques with agroforestry systems is thus very crucial to reduce the competition for water. Rainwater harvesting (RWH) can bridge the mismatch between the rainfall supply and the crop water demand under arid/semi-arid rainfed agriculture. In-situ RWH techniques such as stone bunds, terraces, pits, or trenches are a low cost water management techniques that help retain more water on the soil profile (Biazin et al., 2014; Rosa et al., 2020).

When the soil condition is severely depleted, integrating rainwater harvesting and soil organic amendment (OSA) in to an agroforestry system can increase crop productivity and maintain soil fertility (Kubiku et al., 2022). Organic soil amendment is a process of altering soil characteristics using different soil additives. It has become popular because of its potential to transform or partially replace inorganic fertilizers, low cost and its environmental friendliness (Widowati et al., 2020). Different bio resources have been applied in the literature such as green manure, poultry litter (raw and its bio char), wood ash, straw, mulches, cover crops etc. in order to enhance soil properties, sequester carbon, and increase crop yield (An & Park, 2021; Blair et al., 2014; Management, 2021; Pokhrel et al., 2021). Poultry litter, a mixture of poultry manure and a bedding material from poultry farms has been used for soil amendment due to its high nutrient content (Joardar, 2019). Similarly, Wood ash is often applied to acidic soils as a liming agent and has been reported to increase pH and essential soil macronutrients (An & Park, 2021). For this study, poultry litter, poultry litter biochar and wood ash were used as organic soil amenders to enrich soil nutrient status.

In most parts in Ethiopia, *eucalyptus* is commonly applied agroforestry tree by smallholder farmers mainly due to its economic implications (Alemayehu & Melka, 2022). Despite its popularity, concerns arise due to the high water demand of *eucalyptus* and its

competition for resources when intercropped with annual crops (Mengistu et al., 2022). Thus, incorporating rainwater harvesting and soil organic amendments in to *Eucalyptus globulus* based agroforestry system can provide both ecological and socioeconomic benefits while simultaneously mitigating the concerns associated with resource competition.

An extensive research has been conducted on the separate applications of soil and water management techniques mentioned above. Nevertheless, there is a gap in the literature that analyse the combined effects of the techniques (RWH, AFS, OSA) on soil quality, crop yield and biomass. Very few study exist on combination of rainwater harvesting, agroforestry systems and or soil amendment (Casanova et al., 2021; Zhang et al., 2021; Zhao et al., 2024). The integration of agroforestry systems, rainwater harvesting and soil amendment techniques can have a potential for maintaining soil fertility, increasing crop yield and reducing the risk of food insecurity particularly for smallholder farmers in arid/semi-arid climate (Kugedera et al., 2022). Therefore, the main objective of this research was to determine the combined effect of a *eucalyptus* tree based agroforestry system supported with in-situ rainwater harvesting and organic soil amendment on soil properties, maize & barley yield and analyse the relationship between soil parameters and crop yield.

## 2 Materials and methods

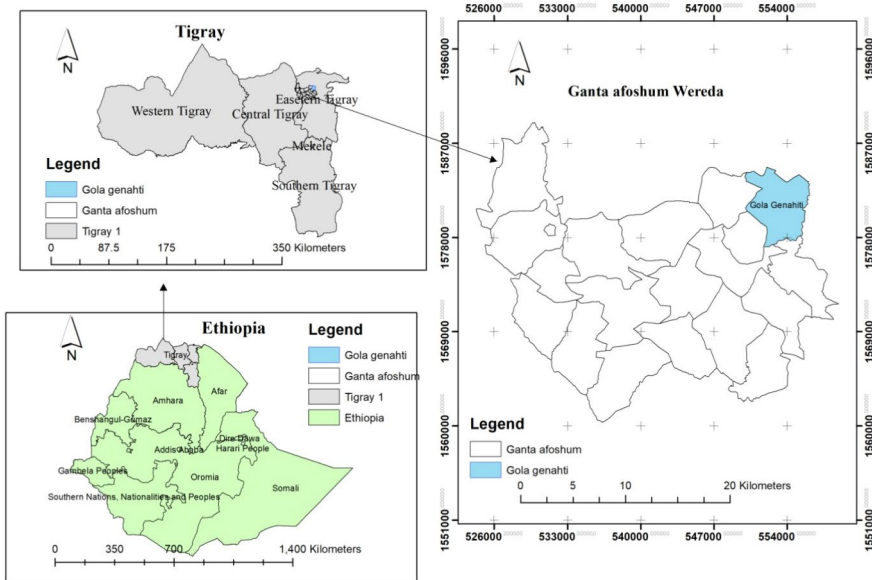
### 2.1 Study area description

The field experiment was carried out in eastern Tigray at Ganta Afoshum district (Fig. 1). The experimental site is a hilly and rugged topography surrounded by scattered *Eucalyptus globulus*. The mean annual precipitation is 565 mm with around  $\frac{3}{4}$  of the precipitation receiving in summer and mean annual temperature is 17.3 °C. It has an area of approximately (750m<sup>2</sup>). Based on processed elevation model, the experimental site had an elevation ranging from 2161 to 2621 m above sea level and a slope ranging from 10 to 15° in the east and northeast directions to steep slopes as high as 70° facing west and southwest direction.

The area contains an integrated agricultural system of crop cultivation and livestock farming. The selection of the experimental site was made based on various biophysical and socio-economic considerations (Debebe et al., 2023) including slope, soil type, run off, catchment area, distance from settlement etc. The soil was characterized as a sandy loam with a moderately acidic nature (pH=5.53). It exhibited low levels of soil organic matter – SOM (0.23%) than the average SOM in the region (Corral-Núñez et al., 2014). In accordance with the guidelines provided by the Ethiopian Agricultural Transformation Agency (Hishe et al., 2017), the soil had low nutrient content and poor water retention capacity. The novel agroforestry system combined three methods namely: (1) In-situ rainwater harvesting (stone bunds and rainwater harvesting pond), (2) soil organic amendment (poultry litter, poultry biochar and wood ash and 3) barley (*Hordeum vulgare L*) - maize (*Zea mays*) – *Eucalyptus globulus* intercropping.

### 2.2 In-situ RWH & supplemental irrigation

Both rainwater harvesting techniques – stone bunds and RWH pond were installed based on the concept of catchment area - cropping area (Oweis et al., 2012). Stone bunding, an

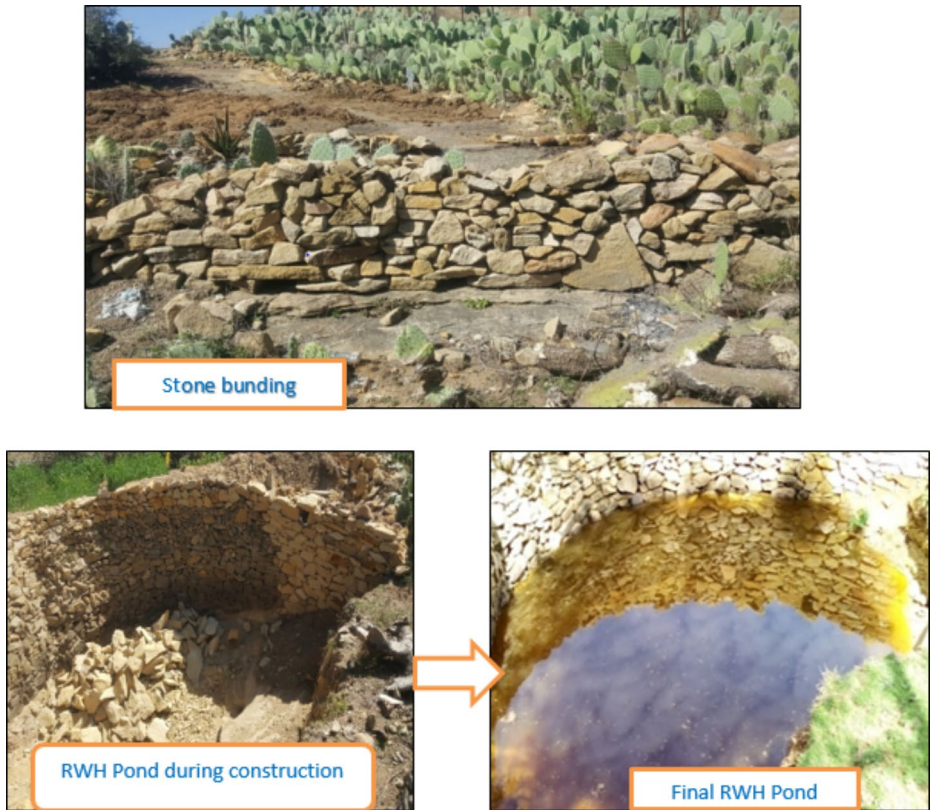


**Fig. 1** Study area map of Gantafoshum- eastern Tigray, Ethiopia

in- situ RWH (5 m long and 40 cm high) was installed using stones at the upper zone in order to slow down the run off volume and prevent soil erosion (Fig. 2). The RWH pond was installed at the foot slope adjacent to the cropping area aimed to store excess run off and serve as supplemental irrigation. The pond had 3 m depth, radius of 5 m and size of 225m<sup>3</sup> (Fig. 2). The bottom part of the pond was rocky surface that hardly infiltrates the water. So, seepage losses to ground water were assumed negligible. The pond was covered using metal sheets to prevent evaporation losses. A total of 33.75 cubic meters of runoff, equivalent to 15% of its full capacity, was collected by the RWH pond during the experiment. This minimal runoff resulted from dry weather from December 2020 to February 2021. The crop water requirement for maize and barley was 600 mm and 500 mm, respectively as per FAO guideline (Anderson & French, 2019). The collected runoff met about 47% of the crops' water needs. The remaining deficit was supplied by transporting water from a nearby hand-dug well. The growing period was 150 days for maize and 120 days for barley, with an average irrigation schedule of 20 mm every five days, totalling 30 irrigation days for maize and 25 for barley.

### 2.3 Soil organic amendment

Poultry litter (raw & biochar) and wood ash were selected as soil amenders due to their local availability, high nutrient content, and potential to replace costly chemical fertilizers. According to Ethiopian ministry of agriculture national poultry development strategy (2022–2031), there is an ever increasing demand for poultry products. Poultry farming expansion has been given a special emphasis at both small scale and industrial level (Fekadu



**Fig. 2** Stone bunding and rainwater harvesting as in-situ RWH methods

et al., 2022). This will increase future availability of poultry manure. On the other hand, based on reports from national agricultural sample survey, 1.92 million tonnes of chemical fertilizer (UREA & NPS) was applied to crop lands in 2020/21 at national level (Central Statistical Agency (CSA), 2021). These chemical fertilizers are imported products that have greater impact on the country's economy. In 2022 alone, Ethiopia imported \$437 M dollar for fertilizers (<https://oec.world/en/profile/bilateral-product/nitrogenous-fertilizers>). Moreover, most small holder farmers cannot afford the soaring price of chemical fertilizers (Alert, 2023). Hence, organic resources such as poultry manure and wood ash can partially substitute the use of chemical fertilizer from both economic and environment point of view. The poultry litter was sourced from a nearby poultry farm, while wood ash was collected from kitchen fuelwood remains. A total of 72 kg of poultry litter and 24 kg of wood ash were collected, sun-dried, and applied to the soil at a rate of 10 tons/ha as in (Joardar, 2019).

## 2.4 Poultry litter biochar preparation

Poultry litter biochar was prepared on site using a traditional earth kiln made of clay and metal. Collected poultry litter (48 kg) was sun-dried and placed in the kiln in six rounds (Fig. 3). The kiln's top was set with a bowl-shaped metal container covered by a metal



**Fig. 3** Producing of poultry litter biochar in an earthen kiln and applying to the soil

**Table 1** Description of treatments used for the experiment and their components

Treatments	Components of treatments in the agroforestry system – AFS
1.PWAFS	poultry litter+supplemental irrigation+AFS
2.BWAFS	Poultry litter biochar+supplemental irrigation+AFS
3.AWAFS	Wood ash+supplemental irrigation+AFS
4.WAFS	Supplemental irrigation, no soil additive+AFS
5.AFS /control	No supplemental irrigation, no soil additive+AFS

sheet. A small opening at the bottom was used for firing. Eucalyptus leaves, barks, and cactus stems served as fuel. The pyrolysis process, taking place in the absence of oxygen, lasted about 3 h. Although the pyrolysis temperature couldn't be directly measured due to limitation in working conditions, the biochar characteristics matched those produced at slow pyrolysis temperatures (Yaebiyo et al., 2023). Slow pyrolysis (250–400 °C) yields higher biochar, organic carbon recovery, and higher functional groups (Cantrell et al., 2012). After combustion, the biochar was cooled naturally, stored in a barrel, and found to have a black, solid texture similar to those reported in the literature (Nair et al., 2017).

## 2.5 Characterization of soil additives

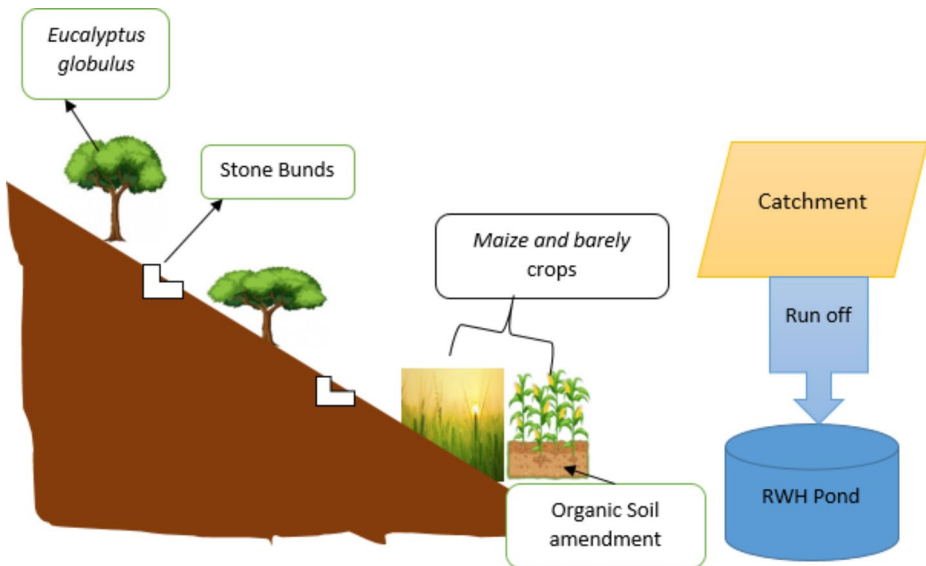
All soil additives were characterized for selected nutrients including organic matter, organic carbon, total nitrogen, and available phosphorus (Motsara & Roy, 2008) at the environmental engineering laboratory – Addis Ababa institute of technology (Table 1). From the three soil additives, poultry litter bio-char had highest SOM, SOC, and Av.P followed by raw poultry-litter and wood ash. Poultry litter had maximum total nitrogen-TN followed by poultry bio-char and wood ash. High alkaline pH values were observed under wood ash and poultry litter bio-char treated soils while raw poultry-litter had a neutral pH. Wood ash contained the lowest soil TN, Av.P and SOM compared to both poultry litter and its biochar.

## 2.6 Eucalyptus – maize – barley – intercropping

The eucalyptus tree-based agroforestry system (Fig. 4) included approximately twenty-five scattered *Eucalyptus globulus* trees, ranging from 1.5 to 7 m height, arranged zonally around both crops (*maize and barley*) on a 750 m<sup>2</sup> area. The spacing between the trees and the crops varied, ranging from as close as 1 m to as far as 10 m. The trees were pruned to minimize resource consumption, and mature trees were regularly harvested. Barley (*Hordeum vulgare*) and maize (*Zea mays*) were sown on the lower zone (Fig. 5). The seeds were pre-soaked for germination and were sown with specified spacing (Farhad et al., 2009; Mutlu, 2021). The field was fenced to prevent grazing, and weeds were manually removed. Crop yield and biomass were estimated using the whole plot harvest method (Fermont & Benson, 2011). Maize ears and barley grains were dried, separated, and weighed for yield and biomass calculations.

## 2.7 Experimental design

The experimental design used was a completely randomized design with five treatments and three replications. This method was chosen because the area had relatively homogenous soil type. Thirty plots each 4 m<sup>2</sup> size [(4 Treatments \* 3 replicates + 3 control) \* 2 crops] were prepared for the field experiment for both crops. The control group is the agroforestry system (AFS) alone that received neither supplemental irrigation nor soil amendment. The other three treatments PWAFS, BWAFS and AWAFS add poultry litter, poultry litter bio-char and wood ash along with supplemental irrigation to the agroforestry system (AFS) respectively. The fourth treatment - WAFS adds only supplemental irrigation but not soil amendment to the AFS. Detailed description of the treatments is presented in Table 1. To



**Fig. 4** Partial Schematic illustration of an integrated eucalyptus based rainwater harvesting - agroforestry system intercropped with maize and barley (Debebe, 2024) image of trees and crops were taken from [www.Freepik.com](http://www.Freepik.com) accessed on 20.10.2023: CC BY 4



**Fig. 5** *Eucalyptus globulus* based small-scale agroforestry system intercropped with *Zea mays* & *Hordeum vulgare* integrated with in situ RWH and organic soil amendment

summarize, the *Eucalyptus globulus* based agroforestry system –AFS is applicable to all the treatments. The difference arises in whether the agroforestry system utilizes supplemental irrigation, organic soil amendment, a combination of both or none at all (control).

## **2.8 Soil sampling and laboratory analysis**

Thirty soil samples were collected from field plots after harvest (150 days for Maize, 120 days for Barley). Four samples were taken from each plot corner at a 0–20 cm depth and mixed to get a homogenized representative soil sample using a systematic sampling tech-

**Table 2** Some characteristics of poultry litter, poultry litter biochar and wood ash

Parameters	Raw PL	PL Biochar	WA
pH	6.90	8.70	9.70
EC (dsm <sup>-1</sup> )	0.21	0.23	0.29
Organic carbon (%)	16.43	21.29	2.28
Organic matter (%)	28.32	36.71	3.94
Total nitrogen (gKg <sup>-1</sup> )	22.63	13.76	45*10 <sup>-3</sup>
Av.p(gKg <sup>-1</sup> )	18.70	26.37	9.15

EC = electrical conductivity,  
 Av.p = available phosphorus, (%  
 = 10 \* g/Kg DM)

nique (Li, 2019). Similarly, three samples were collected from each soil additive (poultry litter, poultry biochar, and wood ash) air-dried, ground, and sieved for nutrient analysis (Table 2). Soil parameters including pH, EC, SOC, SOM, Av.P, and TN were analysed using the updated FAO guideline for soil and plant analysis for moderately acidic soils (Motsara & Roy, 2008) at environmental engineering laboratory, Addis Ababa institute of technology. Soil pH was measured with 1:2.5 soil water ratio using pH meter. Electrical conductivity (EC) was measured by EC meter by preparing 0.01 potassium chloride reagent solution. Soil organic carbon (SOC) was determined by walkey and black wet digestion method. Soil Organic matter - SOM was determined by multiplying SOC by the factor 1.724 assuming SOC comprised of 58% organic matter. Available phosphorus- Av.P was measured using Bray 1 method (Bray & Kurtz, 1945) while total nitrogen was computed by the Kjeldahl method (Nelson & Sommers, 1982). Soil macro and microelements (Ca, Mg, K, Mn, Cu, Fe, Mo, and Zn) were analyzed by ICP-OES at TU Hamburg central laboratory after samples were freeze-dried, ground, and dissolved with Aqua regia-HF.

## 2.9 Statistical analysis

Assumption of normality test was carried out using Shapiro-Wilk test prior to data analysis. The data were analyzed using a statistical package IBM SPSS statistics V26. Variations in selected soil properties & crop yield were analysed between the treatments for significance differences using a one way ANOVA and a *Tuckey test* was used to determine significance difference between treatments at  $P < 0.05$ . The relationship between selected soil chemical properties and crop yield was analysed using Pearson correlation coefficient.

## 3 Result

### 3.1 Soil chemical properties

BWAFS had higher pH value followed by AWAFS and PWAFS at a significance level of  $p < 0.05$ . Both PWAFS and AWAFS had similar positive effect on pH. Conversely, WAFS had non-significant effect on pH ( $P < 0.05$ ) compared to control group- AFS. Maximum and minimum SOM (2.26%, 1.21%) was observed under BWAFS and AFS respectively. Both SOC and SOM exhibited significant variations among all the treatments. BWAFS, PWAFS, AWAFS, WAFS increased SOM by 86%, 27.2%, 16.5% and 5.7% respectively in comparison with AFS (control). Similar to SOM, treatments involving soil amendment and RWH had higher TN and Av.P compared to control group. Particularly, total nitrogen -TN was maximum in PWAFS and minimum in AFS (control). There was no statistically significant

variation observed between BWAFS and PWAFS with TN values 2.9% and 2.7% respectively. Maximum Av.P was observed under BWAFS and minimum under AFS. BWAFS and PWAFS had significant effect on Av.P with increases of 78.1% and 63% relative to the control plots. AWAFS (wood ash &RWH) and WAFS (only RWH) treatments had no statistically significant difference at  $p < 0.05$ .

Maximum Ca and Mg were obtained under BWAFS (biochar &RWH) with increases of 35.5% and 19.2% respectively while AWAFS exhibited minimum Ca and Mg levels. Conversely, both BWAFS and AWAFS treatments exhibited a reduction on potassium level –K. Only PWAFS treatments (poultry litter & RWH) slightly increased K level by 5.2%. BWAFS had maximum Manganese -Mn (10.5% increase) followed by PWAFS. AWAFS and AFS had no significant variation in Mn. Similarly, BWAFS treatments substantially increased copper-Cu by 67% followed by AWAFS (53%), and PWAFS (42%) compared to the control-AFS. PWAFS and BWAFS significantly increased Iron (Fe) by 16% and 10.5% respectively. AWAFS treated soils had no significant effect on Fe. Molybdenum (Mo) and Zinc (Zn) did not exhibit any significant changes among all the treatments (Table 3).

### 3.2 Crop yield and biomass

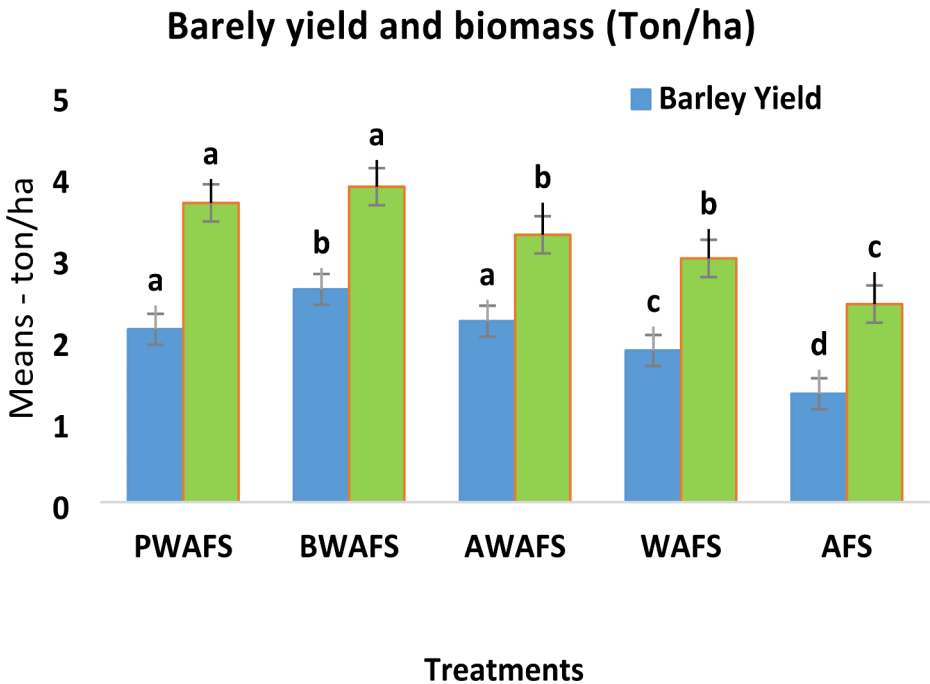
Soils treated with a combination of organic amendments and RWH under *Eucalyptus globulus* based agroforestry systems had significant increases in crop yield and biomass (Fig. 6). Maximum maize biomass was observed under BWAFS (56.5% increase) while minimum maize biomass was observed in WAFS (16.2% increase) relative to the control (Fig. 7). Both PWAFS and AWAFS had a similar effect on maize biomass. Likewise, BWAFS had highest barley biomass (61.5%) whereas minimum barley biomass was found in WAFS (28.5%) at  $p < 0.05$ . Both BWAFS and PWAFS treatments increased maize yield by 74% and 36% respectively. Minimum maize yield was found in WAFS with 6.7% yield increase. No significant change was exhibited between AWAFS and WAFS on maize yield. Barley yield was highly influenced by BWAFS resulting in yield increase of 89.6% followed by AWAFS –62.2% and PWAFS- 57%.

### 3.3 Correlation between crop yield, crop biomass and soil parameters

Positive and strong correlation was observed between crop yield, crop biomass and selected soil properties ( $P < 0.05$  and  $P < 0.01$ ). Yield and Biomass of maize/ barley was strongly and positively correlated with pH, TN and Av.p (Table 4); Positive and moderate correlation was found with SOM. Conversely, Maize yield was less strongly correlated with EC and SOC relative to other parameters.

**Table 3** Means of macro and micro soil nutrients (g/Kg DM or mg/Kg DM)

Treatments	macro nutrients - g/Kg			micro nutrients - mg/Kg				
	Ca	Mg	K	Mn	Cu	Fe	Mo	Zn
Control	3.25	1.68	9.61	0.238	15.00	10.5	<1.3	<250
BWAFS	5.04	2.08	9.59	0.283	25.00	11.6	<1.3	<250
AWAFS	3.66	1.74	9.06	0.236	23.00	10.7	<1.3	<250
PWAFS	3.56	1.98	10.1	0.263	26.00	12.5	<1.3	<250



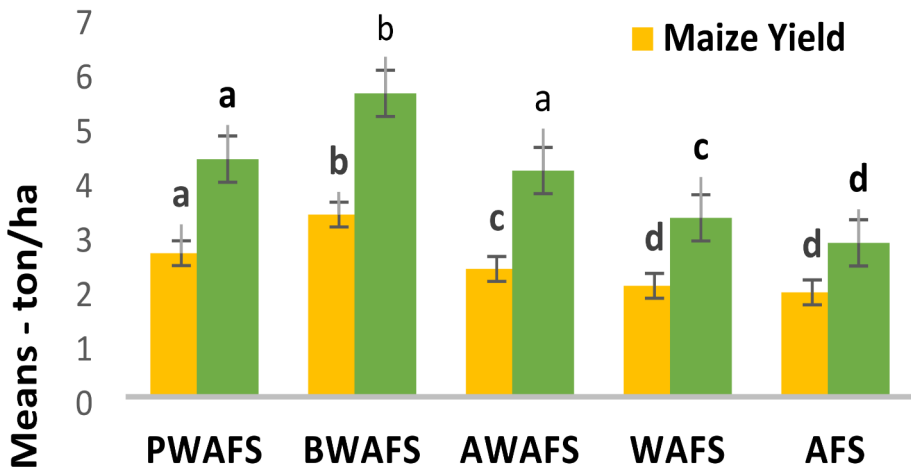
**Fig. 6** Effect of the treatments on barley (*Hordeum vulgare* L) yield & barley biomass. Data are means $\pm$ SE,  $n=3$  means followed by the same letter with in a column are not significantly different from each other at  $p<0.05$ , PWAFS=poultry litter & rainwater harvesting, BWAFS=poultry biochar & rainwater harvesting, AWAFS=wood ash &rainwater harvesting, AFS=Agroforestry system with neither rainwater harvesting nor soil amendment

## 4 Discussion

### 4.1 Soil properties

Soil chemical properties including pH, SOM, SOC, TN, AV.P, macro & micronutrients were positively affected by the combined application of RWH and soil organic amendment under *Eucalyptus globulus* agroforestry system. Similar results were found by (Bhardwaj et al., 2017) which reported positive changes in N, P and K under eucalyptus based agroforestry system. SOM and SOC are important soil attributes for higher crop productivity (Lal, 2014). SOM substantially improves soil chemical, biological and physical characteristics via mobilization of nutrients through SOM decomposition (Corral-Nuñez et al., 2014). Value of SOC/SOM is dependent on factors like climatic conditions (precipitation and temperature) and biotic properties such as quantity & quality of carbon inputs (Luo et al., 2017). Higher SOM values under BWAFS, PWAFS and AWAFS could be attributed to presence of more organic matter inputs and root turnover. These results are in agreement with (Singh et al., 2021) which reported higher soil organic matter on eucalyptus tree based intercropping. The values of SOM and SOC were however low for all the treatments except for BWAFS – biochar &RWH compared to SOM values of farmlands and enclosure areas (2.1 to 5.6) % in the highlands of Tigray (Corral-Nuñez et al., 2014). The higher pH value under treatments

## Maize yield and biomass (ton/ha)



### Treatments

**Fig. 7** Effect of treatments on Maize (*Zea m*) yield and biomass, Data are means  $\pm$  SE,  $n=3$  means followed by the same letter with in a column are not significantly different from each other at  $p < 0.05$ , PWAFS=poultry litter & rainwater harvesting, BWAFS=poultry biochar & rainwater harvesting, AWAFS=wood ash & rainwater harvesting, AFS=Agroforestry system with neither rainwater harvesting nor soil amendment

**Table 4** Pearson correlation coefficient between maize and barley yield, biomass and selected soil parameters

Crop Yield and Biomass	Soil chemical properties					
	pH	EC	SOM	SOC	TN	Av.P
Maize Yield	0.887**	0.496	0.501	0.478	0.904**	0.691**
Maize Biomass	0.876**	0.616*	0.541*	0.558*	0.856**	0.756*
Barley Yield	0.768**	0.692**	0.561*	0.614*	0.709**	0.805*
Barley Biomass	0.826**	0.557*	0.492	0.503	0.885**	0.576*

\*significant at 0.05 level, \*\* Significant at 0.01 level

involving soil amendment might be related to the various soil biogeochemical process such as mineralization of organic matter & metal ions or enzymatic activity that can influence soil pH (Neina, 2019).

The increase in pH of acidic soils can be associated with the availability of alkaline elements with a potential of neutralizing acidic soils (Zolfi-bavariani et al., 2017). A long-term study on combination of poultry litter and walnut tree based agroforestry system also resulted in higher pH value (Sauer et al., 2015). BWAFS & PWAFS treatments involving poultry litter and poultry biochar exhibited higher soil nutrient such as SOM, TN and Av.P compared to AWAFS - treatments that involve wood ash. This could be associated with

**Table 5** Effect of treatments on selected soil fertility indicators

Treatments	pH	SOM (%)	SOC (%)	TN (g/Kg)	Av.p (mg/kg)
PWAFS	5.77±0.06 <sup>a</sup>	1.54±0.00 <sup>a</sup>	0.88±0.01 <sup>a</sup>	2.9±0.03 <sup>a</sup>	21.40±0.00 <sup>a</sup>
BWAFS	6.32±0.14 <sup>b</sup>	2.26±0.01 <sup>b</sup>	1.31±0.00 <sup>b</sup>	2.7±0.04 <sup>a</sup>	23.26±0.01 <sup>b</sup>
AWAFS	5.76±0.18 <sup>a</sup>	1.41±0.02 <sup>c</sup>	0.66±0.00 <sup>c</sup>	1.7±0.02 <sup>b</sup>	19.06±0.01 <sup>c</sup>
WAFS	5.36±0.25 <sup>c</sup>	1.28±0.08 <sup>d</sup>	0.74±0.06 <sup>d</sup>	1.1±0.03 <sup>c</sup>	18.45±0.06 <sup>c</sup>
AFS	5.29±0.03 <sup>c</sup>	1.21±0.00 <sup>e</sup>	0.71±0.01 <sup>d</sup>	0.59±0.04 <sup>d</sup>	13.14±0.05 <sup>d</sup>

Data are means±SE,  $n=3$ , means followed by the same letter with in a column are not significantly different at  $p<0.05$  where PWAFS – (poultry litter & rainwater harvesting), BWAFS (biochar & rainwater harvesting), AWAFS (wood ash, rainwater harvesting), WAFS (rainwater harvesting with no soil additive), AFS (agroforestry system with no rainwater harvesting nor soil amendment)

availability of high organic matter, total nitrogen and phosphorus on both poultry litter and poultry litter biochar (Table 5). According to (Chan et al., 2008), organic soil resources that originated from animal-wastes had higher nutrient amount than their plant derivatives. In addition, the lower TN under AWAFS (wood ash & RWH) could be due related to the very limited nitrogen amount available on wood ash (An & Park, 2021) compared to poultry litter and its biochar. Phosphorus is among the most critical soil nutrients responsible for crop productivity. The combination of soil amendment and RWH had significant positive effect on available phosphorus with higher effects on treatments involving poultry biochar and RWH. This might be attributed to the formation of immobile phosphorus compounds following poultry biochar application and the resulting delayed rapid sorption of phosphorus thus slowly releasing P to the soil (Zhu et al., 2018). Treatments that combined only RWH and agroforestry system (WAFS) also resulted in higher SOC, TN and Av.P compared to the control group- AFS. Similar positive changes in TN and SOC were reported by Salazar et al. (2011) in the drylands of Chile which combined rainwater harvesting and agroforestry systems with similar agroecology. Other study on the Laocess plateau- China combined bio-material amendment from crushed straw and cattle manure with rainwater harvesting in rainfed apple orchard farming reported significant increase soil moisture content and soil structure (Zhang et al., 2021).

BWAFS treatments had notably higher Ca and Mg ions whereas no significant changes were exhibited between PWAFS and AWAFS. These results are in agreement with (Chandra et al., 2020; Gezahegn et al., 2019) which reported higher Ca and Mg ions following soil biochar application. The observed increase in various soil nutrients discussed above could be attributed to the synergistic effect the combined application of organic resources, rainwater harvesting and the litter falls and root turn over from *Eucalyptus globulus* tree. Rainwater Harvesting can favour water retention, facilitate nutrient mobilization and organic matter mineralization (Singh, 2012). Besides, in-situ rainwater harvesting can prevent or reduce massive nutrient losses. A study by Grum et al. (2017) in northern Ethiopia reported up to 80% reduction in soil nutrient losses including TN and Av.P with in-situ rainwater harvesting. Soil organic amendments are also known to supply essential nutrients to the soil leading to higher crop productivity (Chandra et al., 2020; Liu et al., 2017; Pandit et al., 2018).

#### 4.2 Crop yield, biomass & relationship with soil parameters

Yield and biomass of barley (*Hordeum vulgare L*) and maize (*Zea mays*) were positively affected by the combination of RWH and soil organic amendments under *Eucalyptus globu-*

lus agroforestry system. BWAFS (biochar &RWH) showed maximum positive effect on maize yield/biomass (3.39, 5.58 ton ha<sup>-1</sup>) as well as barley yield/biomass (2.56, 3.86 ton ha<sup>-1</sup>) respectively. This could be associated to higher positive net effects of PLB on soil nutrients and the role of in-situ RWH in preventing crop failure finally resulting in higher crop yield. Zhao et al., 2024 reported that integrating rainwater harvesting using optimized ridge furrow techniques with biochar amendment led to increase in fodder crop yield and a decrease in sediment, runoff, and nutrient losses. An increase in *Zea mais* yield was found by (Nyaga et al., 2019) under eucalyptus tree based agroforestry system through managing competition. The calculated maize yield was found to be higher when compared to maize yields with only in-situ rainwater harvesting (Chiturike et al., 2023; Makhlof et al., 2019). AWAFS (wood ash & RWH) did not significantly increased in both maize and barley yield relative to the other treatments. This might be attributed to the limited nitrogen nature of the wood ash (Romdhane et al., 2021). Similar to maize yield/biomass, BWAFS significantly increased barley yield followed by PWAFS, AWAFS, WAFS and AFS- the control. With WAFS, treatments (RWH & AFS) without soil amendment also increased about 6% maize yield and 36.2% barley yield. Barley yields were much higher compared to treatments which solely depend organic amendment (Makhlof et al., 2019; Mutlu, 2021). pH, TN and Av.P had strong positive correlations with crop yield and biomass of both crops. Since pH is among the most dominant soil attributes that determine soil nutrient availability (Moral & Rebollo, 2017), its strong association with crop yield could be that more nutrients were readily taken up by plants that lead to higher yields (Neina, 2019). Similarly, the strong correlation of crop yield and biomass with TN and Av.P could be the indication of the positive influence of these nutrients on crop productivity (Soofizada et al., 2023).

## 5 Conclusions

The combination of RWH and soil organic amendments under *Eucalyptus globulus* tree based agroforestry system positively influenced pH, SOM, TN and Av.P compared to the control. BWAFS significantly increased pH, followed by AWAFS and PWAFS. Soil organic carbon and Soil Organic matter significantly varied among all treatments, with the highest values observed under BWAFS and the lowest in AFS. Similarly, higher TN and Av.P values were observed under BWAFS followed by PWAFS and WAFS. In terms of soil of organic amendments and RWH in the agroforestry system exhibited significant increases in crop yield and biomass. Maize (*Zea Mais*) and barley (*Hordeum vulgare L*) yield & biomass were positively correlated with pH, TN, and Av.P. Overall, the study indicated that combining rainwater harvesting and soil organic amendments with agroforestry system can substantially improve soil fertility and crop yield,. The findings have implications for sustainable organic agricultural practices in the region. From the treatments, addition of poultry litter biochar together with rainwater harvesting has significantly increased crop yield and soil nutrients. In the long term, poultry litter biochar could replace chemical fertilizers which are expensive and environmental unfriendly. Because of its porous structure and high surface area, biochar can retain essential soil nutrients and prevent nutrient leaching (Nair et al., 2017). Poultry litter biochar can be easily produced onsite using simple earthen kilns, making it an ideal choice for smallholder farmers who are unable to afford the increasing costs of chemical fertilizers. In addition to enhancing soil nutrients, poultry biochar can mitigate

climate change by sequestering more carbon during its production. Given the recent surge in poultry farming in Ethiopia (Fekadu et al., 2022), utilizing poultry feedstock can ensure the sustainability of poultry biochar production.

Similarly, installing rainwater harvesting structure can prevent runoff, soil erosion, and crop failure promoting the growth of trees and crops. Incorporating the aforementioned agricultural practices into agricultural policies can pave the way for eco-friendly, sustainable, and low-input farming techniques. However, such agricultural practices can be labour intensive and may require high initial costs for smallholder farmers with resource and financial constraints. Therefore support from government bodies, donors, and other stakeholders is essential. Further research is needed to measure the long-term interaction effects of *Eucalyptus globulus* tree on crop yield & biomass at different seasons before upscaling the system. In addition to measuring soil macro and micro nutrients, it is important to consider other soil health indicators, such as soil microbial activity, for more comprehensive analysis. Finally, Future studies on agroforestry should prioritize tree–crop complementarity with a particular emphasis on leguminous trees due to their role in nutrient acquisition.

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**Data availability** The data used for the study are available up on reasonable request from the corresponding author.

## Declarations

**Conflict of interest** The Authors declare no conflict of interest.

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