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Integrated Effects of Erythrina abyssinica Biomass, NP, and Lime on Soil Acidity Mitigation, Soil Fertility Improvement, and Wheat Productivity in Hula and Bensa Daye, Ethiopia

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ABSTRACT

Nowadays, increasing soil acidity and the resulting decline in soil fertility in the Ethiopian highlands are key factors limiting wheat yield. Therefore, this study was conducted to evaluate the integrated effects of Erythrina abyssinica biomass (EAB), NP, and lime on soil acidity mitigation, soil fertility improvement, and wheat productivity in Hula and Bensa Daye, Ethiopia. Seven treatments were evaluated: control, full EAB dose, half EAB dose + half recommended NP, full lime + full recommended NP, full EAB + full lime + full NP, half EAB + half NP + half lime, and full NP fertilizers. The experiment was laid out in RCB design with three replications. The results showed that the integrated application of Erythrina abyssinica biomass (EAB), lime, and NP significantly influenced soil physicochemical properties and all wheat attributes. At both study locations, improved physicochemical properties, significantly the highest wheat growth, yield, and yield component attributes were obtained from treatment five (TRT5), which received full EAB + full lime + full NP fertilizers. The application of full EAB + full lime + full NP fertilizers increased wheat grain yield by 92.81% over the control at the Hula site. Similarly, at the Bensa Daye site, it increased wheat grain yield by 100% over the control treatment. The findings demonstrate that the integrated application of Erythrina abyssinica biomass, lime, and NP fertilizers improves soil physicochemical properties and enhances wheat performance in acidic soils. Therefore, amending acidic soils with EAB, lime, and inorganic fertilizers effectively mitigates acidity and enhances wheat productivity.

INTRODUCTION

Wheat (Triticum aestivum L.) is one of the most important cereal crops produced and consumed in Ethiopia. It ranks third among cereals in terms of annual cultivated area and grain production, next to barley and tef (CSA 2016). Despite its importance and growing demand for bread wheat in Ethiopia, its production and productivity are desperately low. The average productivity of wheat is below its potential productivity according to the Ethiopia CSA (Central Statistical Agency) reports, such as 2.54 t/ha CSA (2016), 2.74 t/ha CSA (2018), 2.76 t/ha CSA (2019), 3.05 t/ha CSA (2021), and 3.11 t/ha CSA (2022); however, its potential productivity is over 5 t/ha (Silva et al., 2010).As a result, this low wheat productivity scenario requires identifying and addressing barriers to wheat production and productivity in Ethiopia.

Increased soil acidity is one of the key challenges to wheat production and increasing its productivity in the highlands of Ethiopia (Demil *et al*., 2020). Wheat requires substantial amounts of NP fertilizers and other growth nutrients applied for optimum yields (Pandey *et al*., 2020). However, increasing soil acidity in the highlands of Ethiopia is causing a decrease in the effectiveness of N and P fertilizer applications, particularly for cereal crops like wheat. Over 43% of arable land in Ethiopia is affected by moderate to strong acidity (Agegnehu *et al*., 2019), which affects crops that grow on these acidic soils due to direct toxicities from Al^{3+} and H^{+} ions and a lack of nutrient availability. This issue is particularly severe in the highlands, where wheat production is compromised, and in some areas cereal production has been completely abandoned due to strong soil acidity (Haile and Boke, 2009).

Thus, to boost wheat productivity, it is crucial to address soil acidity and low soil fertility simultaneously. Liming is an effective solution to address the challenges of low soil fertility and soil acidity in wheat production. By neutralizing acidity and toxic ions (H^{+} and Al^{3+} ions) in acidic soils, lime application improves nutrient availability, increases the effectiveness of fertilizers, and ultimately enhances crop productivity. Studies in the highlands of Ethiopia have shown that combining lime with nitrogen and phosphorus fertilizers significantly boosts crop yields (Sisay et al., 2026; Agegnehu *et al*., 2019), including wheat yields.

However, subsistence farmers in Ethiopia face challenges in treating soil acidity due to the low production and limited availability of lime (Oumer *et al*., 2023). To address this issue and improve crop productivity, affordable and accessible alternative methods are needed. These alternative options enable the farming society to partially or completely address the soil acidity and soil fertility issues of the affected areas. Organic fertilizers can serve as nutrient sources and be applied alone or in combination with inorganic fertilizers to enhance crop productivity. Integrated application of both types of fertilizers is more effective than using either source alone. Additionally, this approach allows for a reduction in the recommended inorganic fertilizer rates (Haile, 2017).

Identifying and using locally available organic nutrient sources to improve soil fertility and mitigate soil acidity are necessary in the highlands of Ethiopia. One such source is the biomass of *Erythrina abyssinica*, a nitrogen-fixing agroforestry tree whose decomposing litter and root symbiosis enhance soil nitrogen availability and improve soil fertility (Abay, 2018; Musse, 2023; Wolde and Desalegn, 2025) and is widely found in southern, southwestern, and western Ethiopia, including the current study locations (Dagne and Birhanu, 2023). This fast-growing tree produces high biomass and is commonly used as a live fence or farm boundary tree (Haile and Abay, 2013). Analysis of its leaves and twigs showed that nitrogen content ranged from 3.26% to 5.16% on a dry-matter basis, with an average of 4.2% (Haile and Abay, 2013). It also contains phosphorus and potassium at levels comparable to or higher than those of other green manure and agroforestry

trees known for their nutrient content. Its average P and K contents were 0.38% and 2%, respectively (Haile and Abay, 2013). Erythrina biomass is a high-quality green manure that improves overall soil fertility through biological nitrogen fixation, rapid decomposition and mineralization, substantial organic matter contribution, stimulation of soil microbial activity, and enrichment of essential nutrients, particularly nitrogen (N) and phosphorus (P), with substantial potassium (K) content (Berza et al., 2022; Musse, 2023; Berza and Assefa, 2024). Similarly, Abay et al. (2015) report indicates that *Erythrina abyssinica* significantly improves soil fertility by releasing quality chemical constituents as organic sources. Furthermore, field evidence from Ethiopia shows that *Erythrina abyssinica* fresh biomass application significantly increases cation exchange capacity (CEC) and enhances buffering against pH fluctuations (Alemayehu et al., 2017). Generally, as an organic plant nutrient source, the biomass of the *Erythrina abyssinica* holds immense potential for soil fertility enhancement in the region (Gachenge et al., 1999).

However, studies on Erythrina biomass applications in combination with NP and lime are limited in Ethiopia. Similarly, in current study areas such as Hula and Bensa Daye districts in the Sidama region, the use of organic materials like *Erythrina* tree biomass as an organic fertilizer source is not widely practiced to manage acidic soil, prevent acid damage, and enhance crop productivity. Moreover, to date, these districts' farmers have limitations in agronomic technology practices for managing acidic soil to improve productivity. Thus, further research is needed to fully utilize the *Erythrina abyssinica* tree biomass for soil acidity reclamation and improvement of soil fertility. Therefore, this study was conducted to (1) determine the effects of the integrated application of the *Erythrina abyssinica* tree biomass, lime, and NP fertilizers on soil acidity and soil chemical properties, and (2) evaluate the performance of the integrated application of *Erythrina abyssinica* biomass, lime, and NP fertilizers on wheat crop growth, yield, and yield components.

MATERIAL AND METHODS

Description of the study site

The experiment was conducted on a farmer's field in the Hula district and at the Hawassa University Daye Campus research field in the Sidama region in the 2021/2022 cropping season. Hula is situated in the Southern Sidama Zone with geographical coordinates of 6°23'0"-6°39'0" N latitude and 38°27'0"-38°42'0" E longitude (Figure 1). The district is 98 km away from Hawassa city, the capital of the Sidama region. The district's altitude ranges from 2600 to 2800 meters above sea level. The district has a wet, sub-humid climate and a Dega agroecological zone. It receives an average annual rainfall range of 1000 mm to 1300 mm. Its mean annual temperature ranges from 10 to 15°C (SZPEDD, 2010). The soil of this study site is characterized by strong acidity (pH <5.0), low available P, exchangeable K, and organic matter contents (Table 2). Wheat and barley are the two major cereal crops grown in the district, followed by faba bean.

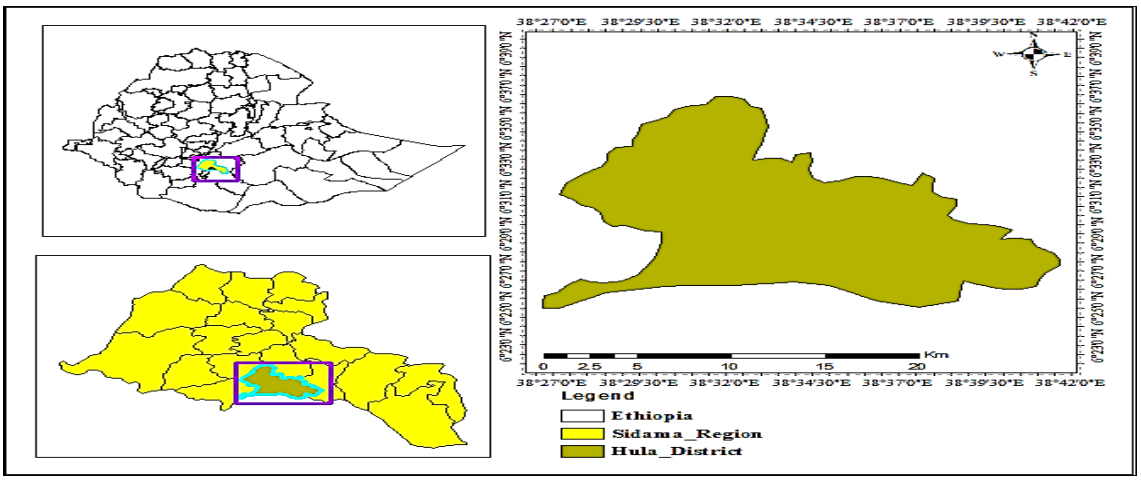

Figure 1 A location map of the study area: Hula district in the Southern Sidama Zone, Sidama Region.

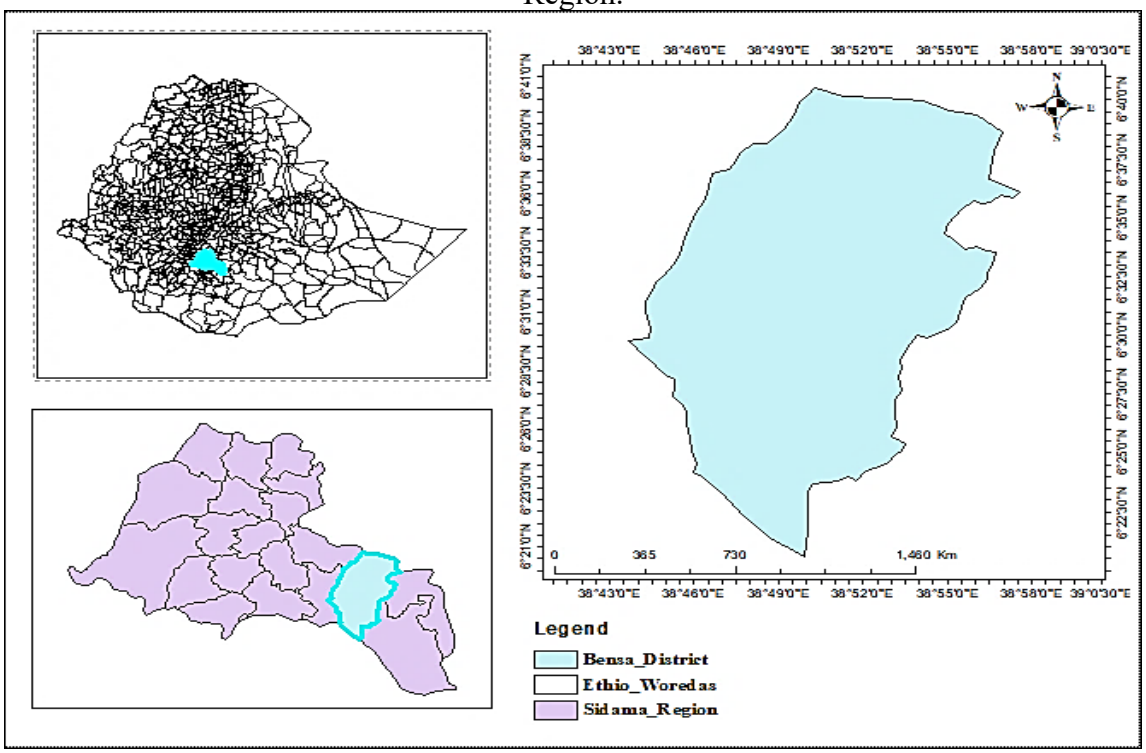

Figure 2 A location map of the study area: Bensa district in the Southern Sidama Zone, Sidama Region.

The Daye Campus research field is located in the Bensa district, Eastern Sidama Zone of the Sidama region. It is 420 km and 130 km away from Addis Ababa, the capital of Ethiopia, and Hawassa city, the capital of the Sidama region, respectively. It has an altitude of 1894 meters above sea level. Its geographical coordinates are 6°21'0"-6°41'0"N latitude and 38°43'0"-39°0'30"E longitude (Figure 2). The area features a sub-humid climate, with an average annual rainfall of 1,208.5 mm and a yearly temperature of 19.0 °C (Bensa District Administration Office, 2018). According to the initial soil analysis results shown in Table 2, the soils of this study location are also characterized as acidic.

Treatments and Experimental Design

In this field experiment, seven treatments were involved: untreated control, Erythrina abyssinica biomass (EAB), NP fertilizers, lime, and their combinations. Table 1 shows the detailed summary of the treatment descriptions. The experiment was conducted in two locations, namely in the Hula district and at the Hawassa University Daye Campus research field, which was laid out in RCBD with three replications.

Table 1. Description of treatments to be tested on acidic soils of Hula and Bensa Daye.

No	Treatments	Rate/Dose		
		EAB (t/ha)	NP (kg/ha)	Lime (t/ha)
1	Control (TRT1)	0	0	0
2	Full EAB dose (TRT2)	10	0	0
3	Half EAB dose + Half recommended NP (TRT3)	5.0	23/10`	0
4	Full Lime + Full recommended NP (TRT4)	0	46/20	5.0
5	Full EAB + Full Lime + Full NP (TRT5)	10.0	46/20	5.0
6	Half EAB + Half NP fertilizers + Half lime (TRT6)	5.0	23/10	2.5
7	Full NP fertilizers (TRT7)	0	46/20	0

Remark: EAB dose applied based on fresh weight basis; NP applied based minimum recommended NP fertilizer dose for the locations, EAB = *Erythrina abyssinica* biomass, NP = Nitrogen and phosphorus fertilizers; TRT1=Treatment 1, TRT2 =Treatment 2, TRT3=Treatment 3, TRT4 =Treatment 4, TRT5 =Treatment 5, TRT6 =Treatment 6, TRT7 =Treatment 7.

Experimental Procedures

The experimental fields were selected, and the land was prepared by ploughing with Oxen twice. The final land preparation activity was accomplished manually using a local farm tool called a hand-held hoe. Then the field layout was prepared; plots were marked, and the plot size was 3.2 x 4 m (12.8 m^2) with a 0.5m interval between plots and a 1 m interval between blocks. The total experimental area size of both locations was 2 x (11.6 x 31 m) = 719.2 m^2.

Following the land preparation and establishment of an experimental layout, leaves and twigs of *Erythrina abyssinica* trees were collected from trees growing at Hula and Bensa Daye districts as live fences, as boundary trees, and as trees growing at the end of individual farmers' fields. Then the collected leaves and twigs of the *Erythrina abyssinica* tree were chopped to a size of less than 5 cm and incorporated into the soils of plots marked to receive EAB treatment at a depth of 0–20 cm. EAB and lime were incorporated into the experimental plots at a depth of 0–20 cm, one month ahead of planting the test crop. Then the Boru wheat variety, ETBW 9554, was planted in each plot with a row spacing of 20 cm apart using a seed rate of 150 kg ha^{-1}. N and P fertilizers were applied along with EAB in each treatment, as a dose was determined for each treatment. Urea and TSP fertilizers were used as sources of nitrogen (N) and phosphorus (P), respectively. Half of the N fertilizer dose was applied at planting; the remaining half of the N dose was applied one month after planting, and at the first crop weeding time. All phosphorus fertilizer doses were applied at the time of planting. Similar management practices were implemented for all treatments throughout the trial period.

Data Collected

Growth parameters and yield and yield comment data, such as plant height (PH), number of leaves per plant (LN), leaf length (LL), leaf area per plot (LA), leaf area index (LAI), spike

length (SPL), number of spikelets per spike (NSPK), number of seeds per spikelet (NSPS), total number of seeds per spike (NSPS), thousand seed weight (TSW), grain yield (GYLD), straw yield (SWY), and biological yield (BY) were recorded for analysis of variance (ANOVA). Before and after harvest, soil data were collected for physicochemical analyses.

Soil Sampling and Analysis

Composite soil samples from the selected experimental fields were collected before planting from a depth of 0-20 cm using an auger, and brought to the laboratory. The samples were prepared, processed, and analyzed for selected physicochemical properties. Similarly, composite soil samples from each plot and treatment were collected after harvest from a depth of 0-20 cm using an auger. The collected samples were sorted by treatment, labeled, and brought to the laboratory, where they were air-dried and milled to pass through a 2 mm sieve. Following this, 1 kg of each processed sample was submitted for analysis of selected parameters.

The physicochemical properties analyzed include soil texture by the Bouyoucos hydrometer method (Bouyoucos, 1962), soil pH in water at a 1:2.5 ratio by pH meter, OC by the Walkley and Black Method (Walkley and Blinedack, 1954), TN by using the Kjeldhal method (Bremner and Mulvaney 1982), available P by using Bray's I method (FAO, 2021). Exchangeable acidity and exchangeable Al 3+ by the titration method (Jones, 2001), exchangeable cations (Na, K, Ca, and Mg), as well as CEC, were determined by the ammonium acetate method (Chapman, 2016).

Statistical Analysis

The collected growth, yield, and yield components data were subjected to ANOVA using SAS software version 9.4 (SAS 2012). The treatment means were separated using the least significant difference (LSD) method at the 0.05 probability level.

RESULT AND DISCUSSION

Before planting, the soil analysis was carried out for both study areas, i.e., Hula and Bensa Daye districts. The initial soil sample analysis results in both study locations showed high exchangeable acidity, high exchangeable aluminium concentrations, and low pH values, indicating acidic soils (Table 2). This may be due to high trivalent aluminium concentration in soil solution at low soil reaction (pH), which is in agreement with the results of Bojórquez-Quintal *et al*. (2017). This occurs because, at low pH, Al dissolves into [Al(H2O)6]3+, which is commonly called Al^{3+} (Vitorello *et al*., 2005; Singh *et al*., 2017). In addition, *Gupta et al*. (2013) and Kisnieriene and Lapeikaite (2015) noted that aluminium-containing minerals dissolve and release trivalent aluminium (Al^{3+}) ions into the soil solution when soil pH drops below 5.5, which contributes to strong soil acidity and is extremely toxic. The initial soil analysis showed a pH value of 4.41 from the Hula site and 5.06 from the Bensa Daye site. Similar to the findings of Hazelton and Murphy (2007), Basu (2011), and ATA (2014), this study's results revealed that the soils of both locations were strongly acidic. Strong soil acidity is a major crop productivity-limiting factor, including wheat, due to aluminum toxicity, phosphorus fixation, and restricted root growth, which ultimately reduce nutrient uptake and grain yield (Kochian et al., 2015).

The initial soil sample analysis results indicate low total nitrogen and available P, according to Olsen and Sommers (1982) and Mugwe *et al*. (2007). According to the findings of Hazelton and Murphy (2007), this low soil available phosphorus, less than 10 mg/kg, is a wheat yield-limiting factor. In agreement with Landon's (2014) report, both study locations (Hula and Bensa Daye districts) also have very low initial soil %OC. Similar to the reports of ATA (2014),

the Hula district soil has low exchangeable potassium (K^+) content, whereas the soil of the Bensa Daye district has moderate exchangeable potassium (K^+) content. Both study locations have soils with medium initial exchangeable (Ca^{2+}) and exchangeable (Mg^{2+}), consistent with the findings of Hazelton and Murphy (2007). Moreover, the initial CEC is low for the Hula district and moderate for the Bensa Daye district (Hazelton and Murphy, 2007). Therefore, to mitigate the negative impact of soil acidity on soil fertility and wheat production, soil amendment with *Erythrina abyssinica* tree biomass, lime, and NP was conducted in the current study locations.

From this study, post-harvest soil sample analysis revealed that the amendment influenced the soil physicochemical properties, highlighting the importance of integrated soil management using *Erythrina abyssinica* tree biomass with lime and NP for crop production in acidic soils (Table 2). In both study areas, the study found that the application of *Erythrina abyssinica* tree biomass (EAB) with lime and NP fertilizers significantly improved soil parameters such as pH, exchangeable cations, cation exchange capacity, exchangeable acidity, exchangeable Al, available phosphorus, organic carbon, and total nitrogen values in acidic soils (Table 2). Similar to the reports of Fekadu *et al*. (2017) and Fekadu *et al*. (2018), the current study suggests that amending acidic soils with EAB organic plant nutrient sources, lime, and NP fertilizers can significantly improve soil physical and chemical properties. This is due to the addition of high plant growth nutrients called Erythrina *abyssinica biomass* (EAB), which can be used to support crop growth and enhance soil fertility, as suggested by previous studies (Haile and Abay, 2013; Alemayehu *et al*., 2017).

In both districts (Hula and Bensa Daye), the pH increased from 4.41 to 5.57 and from 5.06 to 5.81, respectively. This indicates that the soil pH value improved by 26.30% and 14.82% from the control treatment (TRT1) to Full EAB + Full Lime + Full NP (TRT5) in Hula and Bensa Daye districts, respectively. This aligns with Abebe (2018) and Hailu et al. (2025) findings, indicating that increased *Erythrina abyssinica* tree biomass litter fall improves soil chemical properties and raises soil pH, thereby reducing soil acidity through organic matter decomposition and nutrient cycling. This study also showed that using EAB with lime and NP fertilizers substantially improved soil conditions, including Ca, Mg, K, CEC, available phosphorus, OC, and TN, at both the Hula and Bensa Daye locations. This effect is similar to the benefits obtained from the application of organic fertilizers, including legume residues, farmyard manure (FYM), and green manure (GM), which have been widely reported to enhance soil fertility by increasing nutrient availability and maintaining soil organic matter (Sheoran et al., 2025). Similarly, the Gindaba et al. (2005) after-harvest soil analysis study also noted that the application of tree leaf biomass enhanced the concentration of essential nutrients such as available phosphorus, exchangeable potassium (K^+), and total nitrogen (TN). In agreement with these findings, in this study, calcium levels increased from 8.56 to 15.91 cmol(+)/kg (Hula) and 9.09 to 18.48 cmol(+)/kg (Bensa Daye), magnesium from 2.63 to 4.19 cmol(+)/kg (Hula), and 2.74 to 4.56 cmol(+)/kg (Bensa Daye), potassium from 0.479 to 0.85 cmol(+)/kg (Hula) and 0.860 to 1.290 cmol(+)/kg (Bensa Daye), and cation exchange capacity from 11.31 to 26.77 cmol(+)/kg (Hula) and 20.69 to 30.75 cmol(+)/kg (Bensa Daye). Additionally, available phosphorus rose from 3.990 to 21.960 ppm (Hula) and 6.550 to 43.604 ppm (Bensa Daye), organic carbon from 1.753 to 4.075% (Hula) and 1.775 to 4.132% (Bensa Daye), and total nitrogen from 0.120 to 0.23% (Hula) and 0.144 to 0.28% (Bensa Daye). Similarly, the exchangeable acidity level reduced from 0.921 to 0.103 cmol(+)/kg (Hula) and 0.793 to 0.140 cmol(+)/kg (Bensa Daye), and the exchangeable aluminum level reduced from 0.674 to 0.084 cmol(+)/kg (Hula) and 0.571 to 0.121 cmol(+)/kg (Bensa Daye). These findings underline *Erythrina abyssinica* biomass (EAB)'s potential to enhance the productivity and fertility of acidic

soils when integrated with lime and NP fertilizers. The observed improvements in physicochemical properties, including soil pH, exchangeable cations, cation exchange capacity (CEC), available phosphorus, total nitrogen (TN), and organic carbon (OC), as well as reductions in exchangeable acidity and exchangeable Al, may be attributable to the mineralization of *Erythrina abyssinica* biomass and its synergistic effects with lime and NP fertilizers. According to Tiritan et al. (2016), amending acid-affected soils with the combined application of organic matter and lime is more effective than applying plant nutrients alone for mitigating soil acidity and improving soil fertility. Furthermore, Gurmessa's (2021) study also showed that the integrated use of organic fertilizer, mineral fertilizers, and lime is an effective approach to mitigate soil acidity and improve soil fertility.

Similar to the current study results, several research reports indicate that combining organic matter, lime, and mineral fertilizers has a positive impact on soil physicochemical properties. For instance, Bekele *et al*. (2018) demonstrated that the integrated use of compost, phosphorus fertilizer, lime, and farmyard manure significantly improved soil characteristics such as exchangeable bases, cation exchange capacity, soil pH, exchangeable acidity and Al, available phosphorus, and soil organic carbon. Similarly, Bekele *et al*. (2018) found that applying vermicompost, lime, and inorganic phosphorus positively enhanced soil acidity and nutrient availability for crops. Additionally, a study by Ayenew *et al*. (2023) reported that the integration of vermicompost with lime and chemical phosphorus fertilizer effectively improved soil pH, reduced exchangeable acidity, and increased available phosphorus.

At both locations, the study found that all after-harvesting soil physicochemical properties improved under TRT5 when compared to control (TRT1). The highest pH values recorded from the Hula site and the Bensa Daye site were 5.57 and 5.81, respectively. Under TRT5, the study also found maximum values of calcium (Ca = 15.91 cmol(+)/kg from Hula site and Ca = 18.48 cmol(+)/kg from Bensa Daye site), magnesium (Mg = 4.19 cmol(+)/kg from Hula site and Mg = 4.56 cmol(+)/kg from Bensa Daye site), available potassium (K = 0.85 cmol(+)/kg from Hula site and K = 1.290 cmol(+)/kg from Bensa Daye site), cation exchange capacity (CEC = 26.77 cmol(+)/kg from Hula site and CEC = 30.75 cmol(+)/kg from Bensa Daye site), available phosphorus (P = 21.960 ppm from Hula site and P = 43.604 ppm from Bensa Daye site), organic carbon (OC = 4.075% from Hula site and OC = 4.132% from Bensa Daye site), and total nitrogen (TN = 0.23% from Hula site and TN = 0.28% from Bensa Daye site). This indicates that the *Erythrina abyssinica* tree biomass significantly improves soil quality and productivity when applied to acid-affected soils. This suggests that EAB plays a crucial role in improving soil fertility *(*Muzoora *et al*., 2011) by releasing essential nutrients and correcting crop growth nutrient requirements due to its fast decomposition (Abay, 2018). The Paul *et al*. (2015) study similarly found that 10 t ha-1 ipil-ipil tree green leaf biomass applications in the rice production field enhanced the release of total nitrogen (0.178%), available P (30.71 ppm), and exchangeable potassium (K^+).

The highest exchangeable acidity, exchangeable Al, and the lowest calcium, magnesium, available potassium, cation exchange capacity, total nitrogen, and available phosphorus values were obtained from the control (TRT1) and treatments that received half EAB dose + half the recommended NP (TRT3) and a full recommended amount of NP fertilizers (TRT7) when compared to the values obtained from the remaining treatments. When compared to TRT5, the low soil CEC, Ca^{2+}, Mg^{2+}, K^+, %OC, total N, and available P under TRT7 indicate a decreasing response of applied N and P in acidic soil due to Al toxicity, which is consistent with findings of Abate et al. (2013) and Agegnehu *et al*. (2019).

Table 2. Initial and after-harvesting physicochemical soil properties of the study areas.

Location	TRT	pH	EC (ds/m)	Exchangeable Cations ($cmol_c/kg$)				Ex.AC (cmol/kg)	Ex.Al (cmol/Kg)	CEC (cmol/kg)	Avail.P (ppm)	% OC	% TN	% Clay	% Silt	% Sand	Textural class
				Ca	Mg	K	Na										
Bensa Daye	1	5.06	0.163	9.09	2.74	0.860	0.233	0.793	0.571	20.69	6.550	1.775	0.144				
Bensa Daye	2	5.51	0.162	9.87	2.89	1.201	0.281	0.532	0.328	23.57	16.101	2.153	0.151				
Bensa Daye	3	5.30	0.121	9.31	2.77	1.132	0.192	0.781	0.561	23.50	10.442	2.004	0.145				
Bensa Daye	4	5.46	0.154	14.59	3.68	1.191	0.151	0.372	0.268	23.79	23.873	3.813	0.174	8.74	22.91	61.19	Sandy loam
Bensa Daye	5	5.81	0.106	18.48	4.56	1.290	0.135	0.140	0.121	30.75	43.604	4.132	0.280				
Bensa Daye	6	5.64	0.133	16.07	4.09	1.253	0.170	0.224	0.161	24.45	29.563	3.921	0.184				
Bensa Daye	7	5.07	0.162	9.10	2.74	0.914	0.217	0.863	0.602	21.53	11.692	1.755	0.149				
Bensa PPST		5.12	0.169	9.12	2.76	1.022	0.217	0.880	0.606	22.06	6. 864	1.795	0.149				
Hula	1	4.58	0.131	8.56	2.63	0.479	0.141	0.921	0.674	11.31	3.990	1.753	0.120				
Hula	2	5.10	0.113	10.02	3.01	0.488	0.150	0.680	0.434	15.23	14.390	2.104	0.200				
Hula	3	4.41	0.094	8.94	2.69	0.483	0.135	0.921	0.544	14.01	9.361	1.792	0.148				
Hula	4	5.10	0.062	13.23	3.71	0.813	0.127	0.520	0.364	16.63	14.735	3.233	0.220				
Hula	5	5.57	0.044	15.91	4.19	0.850	0.103	0.103	0.084	26.77	21.965	4.075	0.230	22.31	22.84	56.13	Sandy clay loam
Hula	6	5.23	0.071	14.44	4.05	0.814	0.134	0.282	0.196	16.85	17.911	3.262	0.220				
Hula	7	4.93	0.125	8.73	2.67	0.472	0.128	1	0.55	12.43	10.680	1.830	0.120				
Hula PPST		4.88	0.138	9.53	2.89	0.480	0.135	1	0.62	11.92	4.683	1.770	0.147				

Bensa PPST = Bensa Daye Location Pre-Planting Soil Test, Hula PPST = Hula Location Pre-Planting Soil Test, TRT = Treatments, EC = electrical Conductivity, Ca = Calcium, Mg = Magnesium, K = Potassium, Na = Sodium, Ex.AC = Exchangeable Acidity, EX.Al = Exchangeable Aluminium, CEC = Cation Exchange Capacity, Avail.P = Available Phosphorus, OC = Organic Carbon, TN = Total Nitrogen.

The study states that the application of *Erythrina* abyssinica tree biomass (EAB) with lime and NP significantly (P<0.05) influenced the growth parameters of the Boru wheat variety (Table 3), which coincides with the findings of Hasan *et al*. (2019). The results in Table 3 revealed that growth parameters, such as plant height (PH), leaves number per plant (LN), leaf length (LL), and leaf area (LA), significantly improved with the combined use of *Erythrina abyssinica* tree biomass (EAB) with lime and NP fertilizers. This could be because the applied *Erythrina abyssinica* tree biomass (EAB) positively improved soil acidity due to its high essential nutrient content (nitrogen, phosphorus, and potassium) and fast mineralization. This is in line with the study of Abay (2018) who reported that *Erythrina abyssinica* can alter crop nutrient demands due to its quick mineralization. Similarly, Abay *et al*. (2015) indicated that the mean total nitrogen (TN) content was 4.05%, i.e., nitrogen content was higher in *Erythrina abyssinica* litter according to Muzoora *et al*. (2011) and (Haile and Abay, 2013) findings. Haile and Abay (2013) showed that the nitrogen (N), available phosphorus (P), and potassium (K) contents of *Erythrina abyssinica biomass* are 4.2%, 0.38%, and 2%, respectively. In addition, Haile et al. (2009) study on Erythrina leaf and twigs nutrient content analysis noted that 4.83% N, 0.385 P, and 2.245% K in Erythrina biomass.

The study found that treatment five (TRT5) had significantly the highest plant height (PH), leaves number per plant (LN), leaf length (LL), and leaf area (LA) values in both locations compared to the control treatment. The lowest values were observed in the control treatment (TRT1) in both experiment sites. This suggests that integrating organic and inorganic fertilizers can increase productivity in wheat while maintaining soil fertility and health. This is a reason that, as a soil fertility status enhancer, *Erythrina abyssinica* tree biomass can lower soil acidity and supply essential plant nutrients (Haile and Abay, 2013), making it a suitable solution for fast crop nutrient demand correction (Muzoora *et al*., 2011; Haile and Abay, 2013; Abay, 2018). Thus, the results suggest that amending acidic soil with *Erythrina abyssinica* tree biomass can promote soil fertility and reduce land degradation, aligning with previous research reports, such as those of Abreham *et al*. (2022) and Haile *et al*. (2009).

Table 3. Effect of combined application of *Erythrina abyssinica* tree biomass, lime, and NP on ETBW 9554 wheat variety PH, LN, LL, and LA

Treatments	Hula Location				Bensa Daye Location			
	PH (cm)	LN Plant^{-1}	LL (cm)	LA (cm^2) Plot^{-1}	PH (cm)	LN Plant^{-1}	LL (cm)	LA (cm^2) Plot^{-1}
TRT1	57.67^{c}	7.43^{d}	16.13^{e}	61230.04^{d}	62.44^{d}	8.67^{d}	17.43^{d}	65761.24^{d}
TRT2	58.49^{C}	7.57^{d}	16.64^{ed}	75747.76^{d}	65.01^{d}	9.50^{d}	17.70^{d}	83551.8^{cd}
TRT3	59.92^{C}	9.33^{c}	17.53^{d}	80737.92^{cd}	70.34^{c}	10.73^{c}	19.71^{cd}	94905.08^{cd}
TRT4	66.99^{b}	11.43^{b}	19.31^{b}	140014.64^{b}	79.60^{b}	13.17^{b}	22.90^{b}	161288.2^{b}
TRT5	72.39^{a}	13.80^{a}	20.89^{a}	185560.48^{a}	84.90^{a}	15.7^{a}	25.50^{a}	210081.25^{a}
TRT6	64.36^{b}	9.50^{c}	18.56^{cb}	120847.84^{cb}	77.14^{b}	10.77^{c}	20.56^{cb}	126283.64^{cb}
TRT7	65.79^{b}	11.27^{b}	18.70^{cb}	131209.65^{b}	79.34^{b}	12.8^{b}	21.78^{cb}	152807.12^{b}
LSD (5%)	3.32	1.35	1.31	42215	3.98	1.13	2.59	44964
CV (%)	2.93	7.55	4.04	20.88	3.02	5.47	7.01	19.78

TRT1 = Treatment 1, TRT2 = Treatment 2, TRT3 = Treatment 3, TRT4 = Treatment 4, TRT5 = Treatment 5, TRT6 = Treatment 6, TRT7 = Treatment 7.PH = Plant Height, LN = Leaf Number, LL = Leaf Length, LA = Leaf Area.

The amendment of acidic soils in Hula and Bensa Daye with *Erythrina abyssinica* biomass, lime, and NP fertilizers also influenced the leaf area index (LAI) and spike length (SPL) of the Boru wheat crop. Significant variation was observed among treatments in both experiment

locations (Table 4). This may be due to improved soil texture, nutrients, acidity (pH), and bulk density of acidic soil with the amendment of *Erythrina abyssinica* biomass**.** This coincides with the Alemayehu et al. (2017) report, which stated that the improved soil texture, pH, nutrients, and the lowest soil bulk density were recorded under the *Erythrina abyssinica* canopy. Musse's (2023) also found that integrating Erythrina tree biomass with inorganic N fertilizer for wheat production on acidic soil significantly improved soil fertility and increased wheat yield and yield attributes.

Table 4. Effect of *Erythrina abyssinica* tree biomass, lime, and NP combined application on ETBW 9554 wheat variety LAI and SPL

Treatments	**Hula Location**		**Bensa Daye Location**	
	LAI	**SPL (cm)**	**LAI**	**SPL (cm)**
TRT1	0.48^{d}	5.63^{d}	0.51^{d}	6.02^{d}
TRT2	0.61^{d}	5.99^{dc}	0.65^{cd}	6.17^{d}
TRT3	0.63^{cd}	6.32^{c}	0.74^{cd}	7.47^{c}
TRT4	1.09^{b}	7.2^{b}	1.26^{b}	8.78^{b}
TRT5	1.45^{a}	7.87^{a}	1.64^{a}	10.07^{a}
TRT6	0.94^{cb}	6.89^{b}	0.99^{cb}	8.25^{cb}
TRT7	1.03^{b}	7.12^{b}	1.19^{b}	8.75^{cb}
LSD (5%)	0.33	0.48	0.35	1.29
CV (%)	20.63	4.04	19.78	9.14

TRT1 = Treatment 1, TRT2 = Treatment 2, TRT3= Treatment 3, TRT4 = Treatment 4, TRT5 = Treatment 5, TRT6 = Treatment 6, TRT7 = Treatment 7; LAI= Leaf area index, SPL = Spike length.

The study found that significantly maximum leaf area index (LAI) and spike length (SPL) were observed at $p<0.05$ under treatment five (TRT5) in both locations, possibly due to the availability of N and P nutrients for wheat crop leaf area and the increment in SPL as pH increases. The lowest values were obtained from the control treatment (TRT1). The results also stated that TRT1, TRT2, and TRT3 were not statistically different. Similarly, TRT4, TRT6, and TRT7 are statistically in par. Significantly ($P<0.05$), the same mean values were also recorded under TRT3 and TR6. However, in all treatments, the maximum average values of leaf area index (LAI) and spike length (SPL) were obtained from the Bensa Daye location. The results suggest that integrating *Erythrina abyssinica* tree biomass, lime, and NP fertilizers is an effective approach to improve wheat leaf area index (LAI) and spike length (SPL) in acid-affected soils.

Table 5 shows the analysis results for both study locations of spikelets number per spike (NSPK), seeds number per spikelet (NSPS), total seeds number per spike (TNSP), and thousand seed weight (TSW). According to these analysis results, significant variations were observed among the treatments. The analysis results revealed that significantly ($p < 0.05$) high values of NSPK, NSPS, TNSP, and TSW in both study locations were recorded from treatment five (TRT5). Consistent with this study, Paul *et al*. (2015) reported that integrating organic essential plant nutrient sources, such as ipil-ipil tree leaf biomasses, with mineral fertilizers enhances soil fertility and increases crop yield and yield components due to the high essential plant nutrient-releasing capacity of these organic sources. Similarly, Njeri et al. (2021) noted that when the leguminous tree biomass is incorporated into the soil, it contributes N, P, and K plant growth nutrients and organic matter, which enhance soil fertility, water uptake, and soil microbial activity. Moreover, concurrent with current findings, Hasan *et al*. (2019) found that the use of different tree leaf biomass for wheat production significantly enhanced the growth, yield, and yield attributes of

wheat. Significantly, the lowest NSPK, NSPS, TNSP, and TSW values were obtained from the control (TRT1).

Table 5. Effect of Erythrina abyssinica tree biomass, lime, and NP combined application on ETBW 9554 wheat variety NSPK, NSPS, TNSP, and TSW.

Treatments	**Hula Location**				**Bensa Daye Location**			
	NSPK	NSPS	TNSP	TSW	NSPK	NSPS	TNSP	TSW
TRT1	8.9^{e}	2.87^{d}	22.43^{e}	24.80^{d}	10.03^{e}	2.93^{e}	23.13^{d}	30.98^{d}
TRT2	9.77^{ed}	2.93^{d}	24.07^{ed}	26.16^{d}	11.10^{ed}	3.05^{ed}	25.70^{d}	31.12^{d}
TRT3	10.27^{cd}	3.15^{cd}	28.17^{cd}	33.83^{c}	12.30^{cd}	3.42^{cd}	30.57^{cd}	34.42^{cd}
TRT4	11.7^{b}	3.64^{b}	34.33^{b}	40.52^{b}	14.10^{b}	3.85^{b}	41.10^{b}	42.77^{b}
TRT5	12.97^{a}	3.98^{a}	41.97^{a}	46.95^{a}	15.90^{a}	4.27^{a}	50.43^{a}	49.99^{a}
TRT6	11.03^{cb}	3.32^{c}	31.23^{cb}	35.05^{cb}	13.90^{cb}	3.7^{cb}	34.67^{cb}	41.42^{cb}
TRT7	11.6^{b}	3.33^{cb}	33.6^{b}	40.18^{b}	14.10^{b}	3.80^{b}	40.64^{b}	41.10^{b}
LSD (5%)	0.96	0.31	5.06	6.01	1.67	0.37	8.55	7.08
CV (%)	4.97	5.3	9.23	9.56	7.19	5.78	13.66	10.22

TRT1 = Treatment 1, TRT2 =Treatment 2, TRT3=Treatment 3, TRT4 =Treatment 4, TRT5 = Treatment 5, TRT6 = Treatment 6, TRT7 = Treatment 7; NSPK = Number of Spikelets per Spike, NSPS = Number of Seeds per Spikelet, TNSP = Total Number of Seeds per Spike, TSW = Thousand Seed Weight.

The current study results in Table 6 show that wheat grain yield (GYLD) was significantly ($p< 0.05$) improved from 2.324 to 4.48 t/ha (Hula district) and 2.588 to 5.199 t/ha (Bensa Daye district) with integrated application of *Erythrina abyssinica* tree biomass, lime, and NP fertilizers. Similarly, according to Asrat *et al*. (2014), the integrated amendment of acidic soil with organic fertilizer (manure), lime, and inorganic P fertilizer significantly resulted high grain yield of wheat. Haile *et al*. (2009) study showed increased wheat grain yield with the combined application of the Erythrina tree biomass and NPK fertilizers. Abreham *et al*. (2022) also stated a statistically significant difference in wheat grain yield due to the combined use of organic plant essential nutrient sources, such as *Erythrina abyssinica* biomass with lime and NP fertilizers. Moreover, Musse (2023) reported enhanced wheat grain yield due to the integrated use of *Erythrina* biomass and mineral N fertilizer. In contrast to Abreham *et al*. (2022), straw yield (SWY) and biological yield (BY) showed significant variation in both experiment locations (Table 6). A treatment (TRT5) that received full EAB, full lime, and full NP fertilizer rates produced significantly ($P<0.05$) high mean GYLD, SWY, and BY as compared with the control and the remaining treatments. It coincides with Ameyu and Tola's (2024) results, which stated that organic fertilizers such as vermicompost, integrated application with lime, and inorganic NP fertilizers significantly increased wheat biomass and grain yields.

The lowest grain yield (GYLD), straw yield (SWY), and biological yield (BY) under the control treatment may be due to the extreme soil acidity's impact on phosphorus fixation. The reason is that the P-fixation ability is very high in acidic soil (Agegnehu *et al*., 2021). This situation causes a deficiency of available phosphorus in the soil for plant uptake (Hazelton and Murphy 2007) and reduced wheat yield (Abreham *et al*., 2022). In both study locations, the mean grain yield (GYLD), straw yield (SWY), and biological yield (BY) produced under treatments four (TRT4), six (TRT6), and seven (TRT7) did not indicate significant variation. Similarly, no significant difference was observed among treatments TRT1, TRT2, and TRT3. Similarly, the study showed that nonsignificant wheat biomass and grain yield were observed with the

application of NP mineral fertilizers under acidic soils due to the influence of soil acidity (Abreham *et al*., 2022).

Table 6. Effect of Erythrina abyssinica tree biomass, lime, and NP integrated use on ETBW 9554 wheat variety grain yield (GYLD), straw yield (SWY), and biological yield (BY).

Treatments	Hula Location			Bensa Daye Location		
	GYLD (t ha^{-1})	SWY (t ha^{-1})	BY (t ha^{-1})	GYLD (t ha^{-1})	SWY (t ha^{-1})	BY (t ha^{-1})
TRT1	2.324^{c}	2.037^{d}	4.361^{c}	2.588^{d}	2.819^{d}	5.407^{d}
TRT2	2.353^{c}	2.443^{cd}	4.797^{c}	2.696^{d}	3.229^{cd}	5.925^{d}
TRT3	2.598^{c}	2.732^{cd}	5.329^{c}	3.307^{cd}	3.238^{cd}	6.544^{cd}
TRT4	3.970^{b}	4.379^{b}	8.349^{b}	4.292^{b}	4.450^{b}	8.742^{b}
TRT5	4.481^{a}	5.513^{a}	9.994^{a}	5.199^{a}	6.693^{a}	11.892^{a}
TRT6	3.570^{b}	3.557^{cb}	7.127^{b}	4.141^{cb}	4.081^{cb}	8.222^{cb}
TRT7	3.846^{b}	4.159^{cb}	8.005^{b}	4.283^{b}	4.386^{b}	8.668^{b}
LSD (5%)	0.503	1.133	1.477	0.865	1.054	1.684
CV (%)	8.56	17.97	12.12	12.85	14.36	11.96

TRT1 = Treatment 1, TRT2 = Treatment 2, TRT3 = Treatment 3, TRT4 = Treatment 4, TRT5 =Treatment 5, TRT6 =Treatment 6, TRT7 =Treatment 7; GYLD = Grain Yield, SWY = Straw Yield, BY = Biological Yield, HI = Harvest Index, LSD (5%) = Least significance Difference at 5% Probability Level, CV = Coefficient of variation.

CONCLUSION

The results of this study showed that the combined amendment of *Erythrina abyssinica* biomass, NP fertilizers, and lime improved soil fertility and wheat productivity in Hula and Bensa Daye districts. Soil acidity decreased and physicochemical properties of the soil improved in both study locations due to the combined application of *Erythrina abyssinica* biomass, NP fertilizers, and lime. Significant variations were also observed in plant growth parameters, crop yield, and yield components. From both study districts, the highest plant height (PH), leaves number per plant (LN), leaf length (LL), leaf area (LA), leaf area index (LAI), spike length (SPL), number of spikelets per spike (NSPK), number of seeds per spikelet (NSPS), total number of seeds per spike (TNSP), thousand seed weight (TSW), grain yield (GYLD), straw yield (SWY), and biological yield (BY) recorded from treatment five, which received full dose of Erythrina abyssinica (EAB) + full dose lime + full doses of nitrogen and phosphorus fertilizers (NP) rates. Thus, the adoption of an integrated application of *Erythrina abyssinica* tree biomass, NP fertilizers, and lime is an important practice for reclaiming soil acidity and enhancing soil fertility in the Hula and Bensa Daye districts of the Sidama region, as well as in similar areas, to boost crop production on acidic soils.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to the publication of this paper.

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