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Growth and phenological responses of selected improved coffee varieties (*Coffea arabica* L.) to Vermicast application

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Abstract

Organic soil amendment is important for sustainable coffee production; however, efforts to establish its scientific basis have been insufficient. This study evaluated the phenological and growth responses of selected CBD-resistant coffee varieties to different vermicast application rates at Wonago, Gedeo, during 2022–2023 under irrigation. A 4 × 6 pot experiment was arranged in a randomized complete block design with three replications. Treatments consisted of four coffee varieties (74112, 74110, Kotti, and Fayate) and six levels of cow dung vermicast (4.5, 6.3, 8.1, 9.9, and 11.7t ha^{-1}, plus a control) were considered as treatments. ANOVA showed that both variety and vermicast significantly affected seedling girth, number of primary branches, leaf number, leaf chlorophyll content, leaf area, specific leaf area, primary branch length, biomass, and dry weight of seven-month-old coffee seedlings. In addition, node number, seedling height, and days to 50% emergence were significantly influenced by the interaction between variety and vermicast. Variety Kotti exhibited the highest biomass, seedling girth, leaf chlorophyll content, leaf area, and specific leaf area, possibly in relation to this variety is native to the study area, while variety 74112 produced the highest number of primary branches, primary branch length, leaf number, and seedling dry weight. Application of 9.9 and 11.7t ha^{-1} vermicast shortened the number of days to first emergence and 50% emergence. As the vermicast rate increased up to 9.9t ha^{-1}, seedling growth improved for most parameters; however, when the rate exceeded 9.9t ha^{-1}, a slight decline was observed, possibly because some growth regulators in the vermicast became dominant in the growth process. Further studies are suggested to determine the levels and types of growth hormones present in cow dung vermicast.

Keywords/Phrases: Growth, Phenology, Varieties, Vermicast

1 Introduction

In Ethiopia, more than 22 million people depend directly or indirectly on coffee for their livelihoods (Sisay, 2018; Woyesa & Kumar, 2021). Approximately 95% of the country's coffee is produced by smallholder farmers, who often face shortages of production inputs and improved technologies required for efficient coffee production (Dida, 2022; Sarirahayu & Aprianingsih, 2018).

In addition, Ethiopian coffee production is constrained by multiple factors, including climate change, poor postharvest handling practices, settlement and resettlement activities, deforestation, low market returns, and inadequate nutrient management (Dida, 2022; Tadesse *et al*., 2020). Among these constraints, nutrient management is one of the most important determinants of coffee productivity and sustainability across different production systems (Wang *et al*., 2015).

Commercial coffee farms generally adopt better nutrient management practices than garden and semi-

forest coffee production systems. In forest coffee production, nutrient supply relies mainly on natural soil amendments such as humus and green manure. However, as in other agricultural lands, soil fertility in many Ethiopian coffee-growing areas has been declining at an alarming rate, requiring substantial intervention to maintain productivity (Maryo *et al.*, 2025; Netsere & Takala, 2021; Tadesse *et al.*, 2020). Deficiencies of essential micronutrients, including zinc (*Zn*), copper (*Cu*), boron (*B*), and molybdenum (*Mo*), have been reported in several coffee-growing regions of the country (Maryo *et al.*, 2025; Netsere & Takala, 2021).

Recently, vermicast has been reported as an excellent source of nutrients and has been shown to improve plant height, leaf number, stem circumference, and leaf area of Robusta coffee seedlings during the three- to six-month growth period (Adhikary, 2012). Beyond nutrient management, coffee variety is also an important factor influencing coffee growth and yield performance (Fufa *et al.*, 2020). Nevertheless, the individual and interactive effects of vermicast application and varietal differences on coffee growth and development have not been adequately examined. Therefore, the present study aims to evaluate the effects of vermicast, coffee varieties, and their interactions on the phenological and growth responses of coffee seedlings.

2 Materials and Methods

The study was conducted at Tumata Chirecha, Wonago, in the Gedeo Zone, on the coffee research farm of the College of Agriculture and Natural Resources, Dilla University. A 4×6 factorial pot experiment was laid out in a randomized complete block design (RCBD) and replicated three times. The treatments consisted of four coffee varieties (74112, 74110, Fayette, and Kotti) obtained from the Jimma Agricultural Research Center, and six rates of cow dung vermicast (4.5, 6.3, 8.1, 9.9, and 11.7$t\ ha^{-1}$) plus a control; these were the two factors studied.

Data were collected on days to first emergence, days to 50% emergence, stem/seedling height at transplanting (cm), number of leaves per plant, specific leaf area (SLA), total leaf area (LA), stem girth (cm), number of primary branches, main branch length, total chlorophyll content, tap root length, biomass yield (g), and total dry weight (g). The collected data were checked for normality using univariate analysis and then subjected to two-way analysis of variance using Statistical Analysis System (SAS) software version 9.4.

Soil Analysis: Soil samples were taken in composite form across the potting media by mixing soils that received the same vermicast rate. The analyses included percentage of organic carbon (OC), percentage of organic matter (OM), available phosphorus (Av. *P*), total nitrogen (TN), cation exchange capacity (CEC), soil pH, and textural class of the media. For all parameters, the procedures were followed according to the (SRD, 2014) soil analysis manual.

3 Results and Discussion

3.1 Effect of vermicast rates on number of days to emergency

Vermicast rate significantly ($P \leq 0.05$) affected the number of days to first emergence. The shortest time to emergence after sowing (44.26 days) was recorded at *R*5(11.7$t\ ha^{-1}$), followed by *R*4(9.9$t\ ha^{-1}$). In contrast, the longest time to emergence (52.99 days) was recorded in the control treatment (*R*6), representing increases of 19.7%, 13.4%, and 12.8% compared to *R*5, *R*4, and *R*3 (8.1$t\ ha^{-1}$), respectively (Figure 1). The shorter time to emergence observed in seedlings treated with the highest rate of cow dung vermicast may be attributed to enhanced seed germination (Nagavallemma *et al.*, 2004). This effect could be associated with increased soil temperature resulting from microbial activity stimulated by earthworm casts (Govindapillai *et al.*, 2018). In addition, improved physicochemical properties of the growing medium—such as increased concentrations and availability of ammonium and nitrate—may help break seed dormancy. Vermicast also improves the moisture-holding capacity of the growing medium (Arancon *et al.*, 2003; Hilhorst & Karssen, 2000).

The findings of the present study are consistent with those of previous research (Arancon *et al.*, 2005; Edwards *et al.*, 1988), which reported that vermicast application significantly improved the emergence of tomato, radish, and cabbage seedlings.

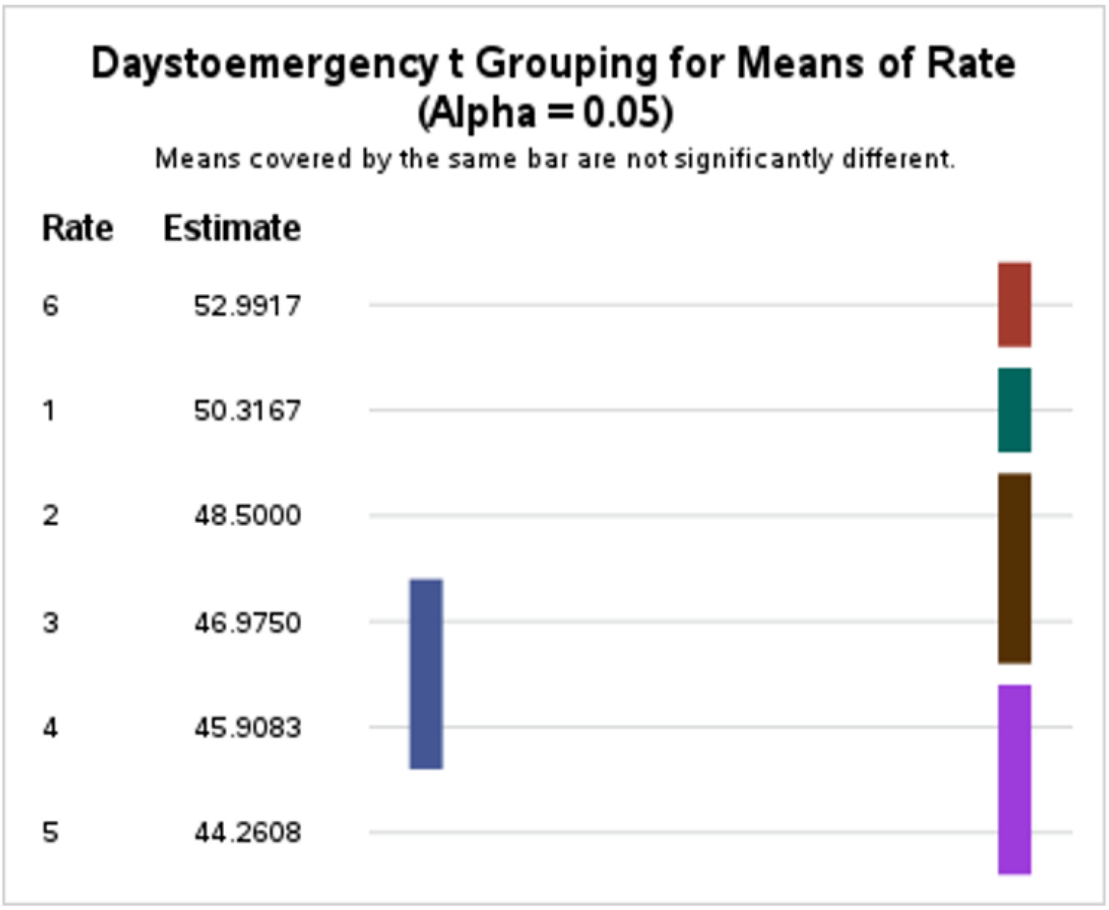


Figure 1. Effects of cow dung Vermicast rate on days to first emergency

3.2 Effect of coffee variety and vermicast rate on number of days to 50% emergency (D50E)

The interaction between coffee variety and vermicast rate significantly ($P \leq 0.05$) affected the number of days from sowing to 50% seedling emergence. The shortest time to 50% emergence (49 days after sowing [DAS]) was recorded from the combination of the Kotti variety and 11.7$t\ ha^{-1}$ ($R5$) vermicast, followed by 74110 $\times$ 11.7$t\ ha^{-1}$ (50.96 DAS), Kotti $\times$ 9.9$t\ ha^{-1}$ (51.00 DAS), and Fayyetae $\times$ 11.7$t\ ha^{-1}$ (51.50 DAS). In contrast, the longest time to 50% emergence was observed in the combinations of 74112 with $R6$ (control) and $R1$, respectively (Figure 2). Increasing the vermicast application rate by at least 15% reduced the number of days required to reach 50% emergence by up to 24%. This reduction may be attributed to enhanced soil temperature resulting from increased microbial activity stimulated by earthworm casts (Govindapillai *et al*., 2018), improved nutrient-use efficiency of the coffee varieties, and increased availability of ammonium and nitrate, which facilitate seed germination and early seedling establishment (Arancon *et al*., 2003; Hilhorst & Karssen, 2000). In addition, vermicast contains higher concentrations of humic substances. Humic acids are known to regulate plant growth by influencing hormonal signaling and physiological response pathways, thereby promoting seed germination and early seedling development (Aline *et al*., 2022; Keiji Jindo, 2020; Norman *et al*., 2006).

The results of the present study are consistent with those reported by Arancon *et al*. (2003) and R.M. Atiyeh *et al*. (2000), who found that vermicast application significantly improved seed germination and several early growth parameters through enhanced nutrient availability and improved soil conditions.

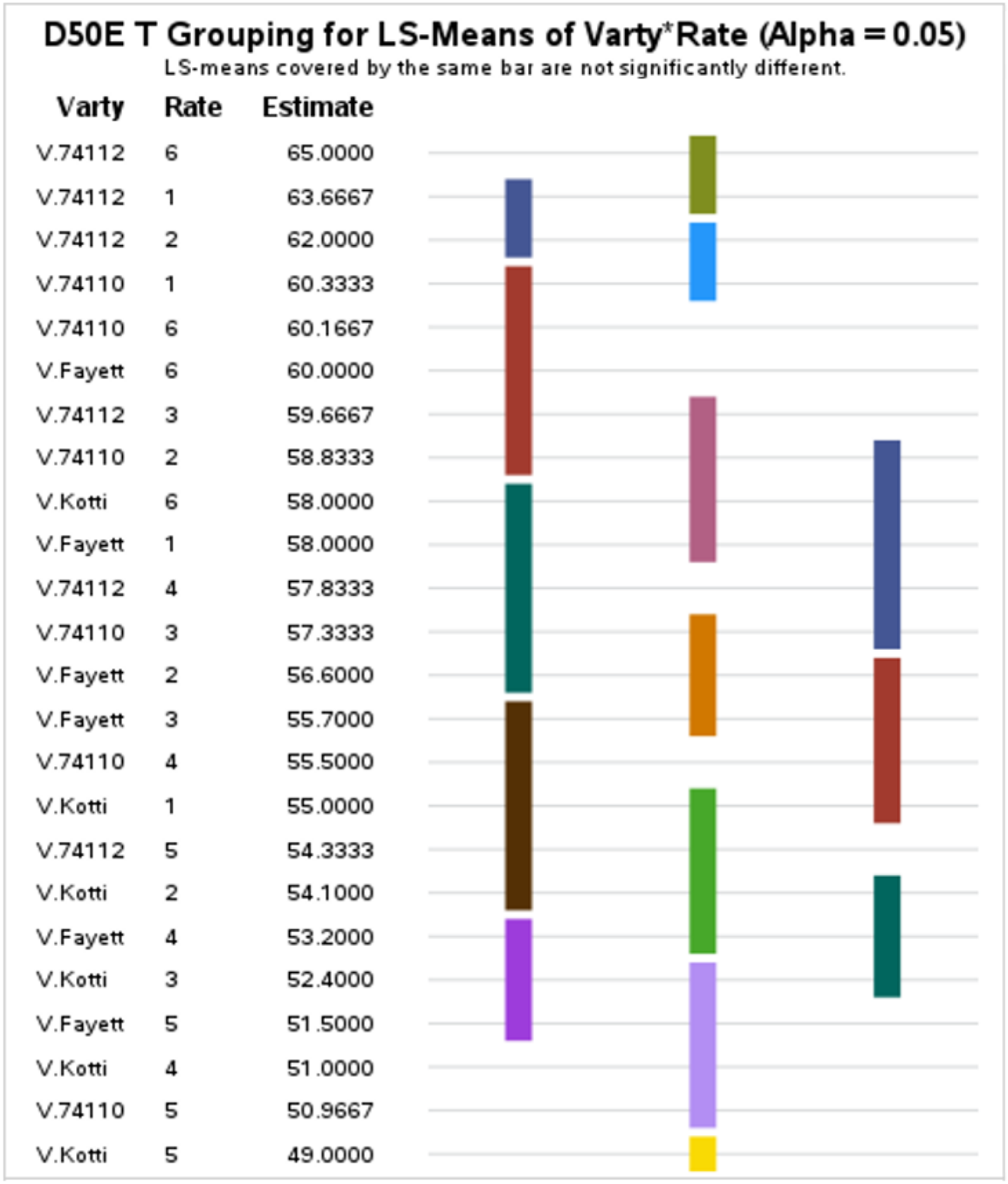


Figure 2. Interaction effect of variety and Vermicast on number of days to 50%

3.3 Effect of Coffee variety and Vermicast rate on the Number of nodes and Seedling height

The interaction between coffee variety and vermicast rate significantly ($P \leq 0.05$) affected the number of nodes (NN) and seedling height (SH). The highest number of nodes (8.0 and 7.9) and seedling heights (53.75 and 53.33*cm*) were recorded in the combinations of Fayette $\times$ *R*4 and 74112 $\times$ *R*5, respectively (Figure 3A and 3B).

Variety Kotti showed the highest response to the greatest vermicast rate for the variables NN and SH, compared with all varieties evaluated in the experiment, except variety 74112. This difference may be associated with the genetic potential of Kotti to utilize phytohormones that may be generated through interactions between microorganisms in the rhizosphere and earthworms in vermicast.

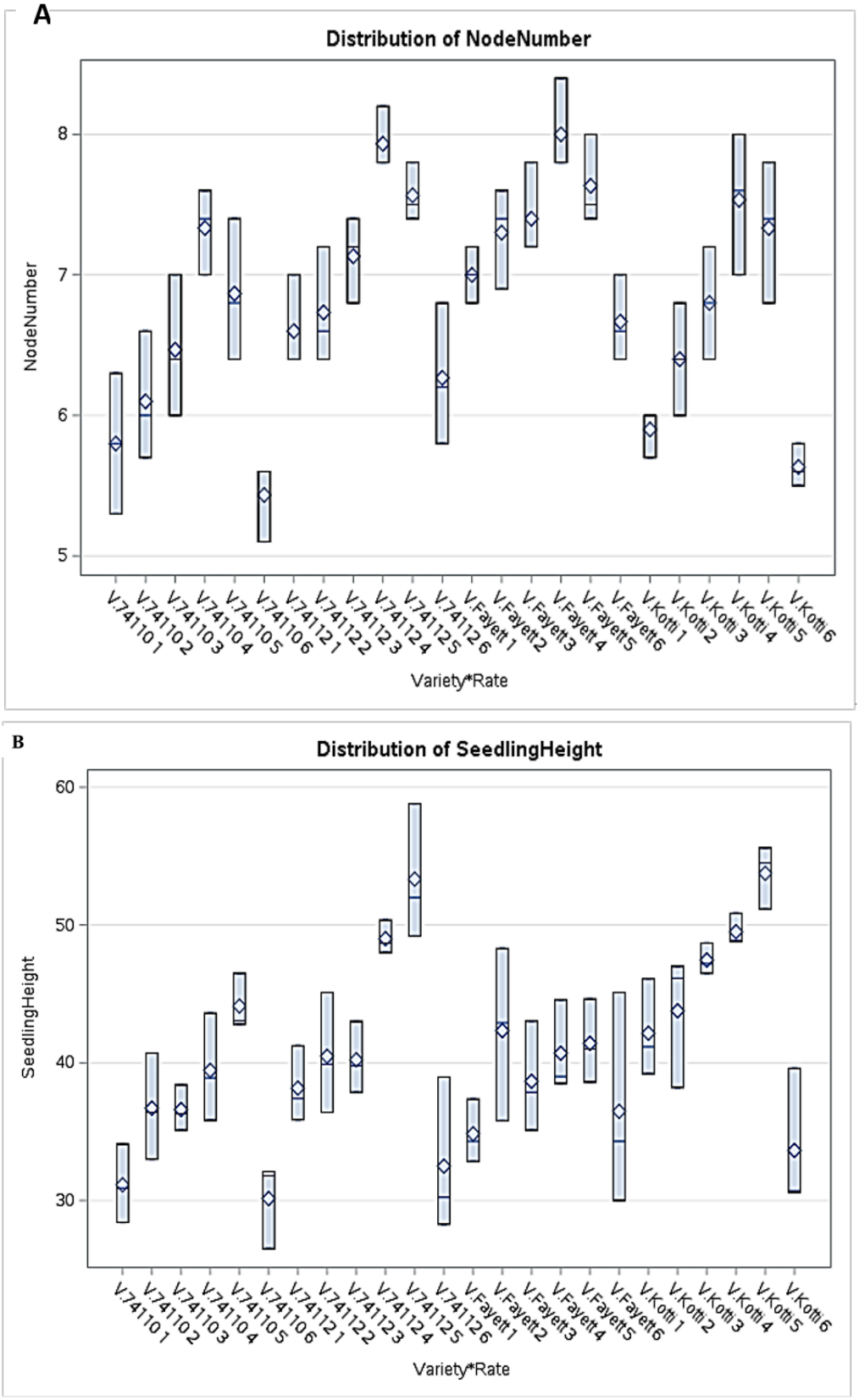


Figure 3. A: Interaction effect of coffee variety and Vermicast rate on Number of Node and height of 7 months aged coffee seedlings; **B:** Number of Node and height of 7 months aged coffee seedlings

Among the coffee varieties tested, Kotti also exhibited a greater response to the highest vermicast rate with respect to both number of nodes and seedling height, although its performance was comparable to that of 74112. The variation in response may be due to differences in the genetic capacity of coffee varieties to utilize growth-promoting substances present in vermicast. Vermicast is known to contain phytohormones and beneficial microorganisms that interact in the rhizosphere, thereby improving nutrient uptake and enhancing plant growth (Rehman *et al*., 2023).

The findings of the present study are in agreement with those reported by Atiyeh *et al*. (2002) and R.M. Atiyeh *et al*. (2000), as well as Govindapillai *et al*. (2018) and Norman *et al*. (2006), who found that vermicast significantly increased the number of nodes and plant height compared with farmyard manure, conventional compost, chemical fertilizer, and commercial synthetic plant growth hormones.

3.4 Effect of coffee variety and vermicast rate on Seedling Girth

Regarding the main effects, both factors significantly ($P \leq 0.01$) affected coffee seedling girth independently. For the variety factor, the thickest seedling girth (4.45cm) was recorded from variety Kotti, followed by 74112 (4.19cm) and Fayette (3.90cm). In contrast, the least seedling girth was obtained from variety 74110, which deviated by 20.2%, 15.3%, and 8.97% from varieties Kotti, 74112, and Fayette, respectively.

Concerning vermicast rate, the highest mean seedling girth (4.64cm)was observed in seedlings treated with $R5$, followed by $R4$, which was statistically comparable with $R3$. The lowest seedling girth was recorded in the control treatment (Table 1).

In living coffee plants, seedling girth is an important indicator of potential crop performance in terms of overall growth and yield. Therefore, only well-vegetatively grown coffee seedlings can achieve good transplanting quality and field establishment. The probable reason for the greater seedling girth observed in variety Kotti may be its genetic capacity to tolerate environmental conditions such as temperature, humidity, and radiation (Debela & Ayalew, 2018), as well as the effects of the vermicast rates applied (Arancon *et al*., 2003; Govindapillai *et al*., 2018).

The present findings are consistent with those reported by Atiyeh *et al*. (2002), R.M. Atiyeh *et al*. (2000), and Norman *et al*. (2006), who found that using vermicast as a nutrient source, either alone or combined with other organic or inorganic fertilizers, increased most growth parameters compared with other fertilizer sources. In addition, the presence of readily available nutrient forms in vermicast —such as NO_3, exchangeable phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) —may further explain the superior performance of vermicast-treated coffee seedlings (Arancon *et al*., 2005; Arora *et al*., 2011; Edwards *et al*., 1988).

3.5 Effect of coffee variety and vermicast rate on Primary Branch number

Seedling branch number is one of the most sensitive indicators of variation among varieties and environmental conditions (Atinafu & Mohammed, 2017). It also determines the crop's yield potential; therefore, differences in the number of primary branches (NPB) among varieties reflect differences in potential growth and yield.

The analysis of variance showed that variety had a highly significant effect ($P \leq 0.01$) on NPB. The observed mean NPB ranged from 1.41 to 2.54 (Table 1). The highest NPB was recorded for variety 74112, whereas the lowest NPB was observed in variety 74110.

Regarding vermicast rates, the highest mean NPB (3.26) was recorded in $R4$, followed by $R5$(2.53). The minimum NPB was obtained from the control treatment (Table 1). Overall, the mean NPB of all vermicast-treated 7-month-old seedlings increased by 54% compared with the control. This improvement may be attributed to enhanced nutrient availability —particularly nitrogen —and the presence of growth-regulating hormones involved in vegetative growth (Arora *et al*., 2011; Debela & Ayalew, 2018; Edwards *et al*., 1988; Govindapillai *et al*., 2018).

According to the review by Theunissen *et al*. (2010), nitrogen plays key roles in several physiological pro-

cesses, including photosynthesis, cell division and differentiation, growth and somatic embryogenesis, chlorophyll content, Rubisco activity, and electron transport rate.

3.6 Effect of coffee variety and vermicast rate on Number of Leaf

Leaf is a vegetative part of the plant where several physiological processes occur, including photosynthesis, respiration, transpiration, phototropism, and photophosphorylation (Faujiah *et al*., 2023). Therefore, increases or decreases in the number of leaves directly influence coffee growth and yield.

Results from the analysis of variance for the main effects indicated that variety had a highly significant effect ($P \leq 0.01$)on the number of leaves (NL). The mean NL among the varieties used ranged from 13.66 to 18.93 (Table 1). The findings of this study showed that variety 74112 had the highest NL, followed by Fayette (16.38). In contrast, variety 74110 produced the lowest mean NL, which differed by 27.8% from variety 74112.

The analysis of variance also showed that vermicast rate had a highly significant effect on NL. The highest mean NL (18.93) was recorded in seedlings treated with *R*4, followed by *R*5(17.55). The lowest NL (12.93) was obtained from seedlings treated with *R*6. The probable reason for the higher NL in the plants treated with larger vermicast rates may be related to the availability and concentration of growth-regulating substances, such as ethylene and cytokinin, which are involved in cell division and differentiation (Abdallah *et al*., 1986; Grapelli *et al*., 1985).

The findings of the present study are consistent with those reported by Indrakumar and Chauhan (2009), who found that vermicast-treated plants performed best compared with inorganic nutrient sources, farmyard manure, and mixtures of these. Similarly, Nijhawan and Kanwar (1951) reported that plants treated with vermicast produced higher mean values than other treatments. Govindapillai *et al*. (2018) also reported that 50% vermicast-treated *Capsicum annuum* (L.) plants showed the best mean leaf number compared with other plant growth enhancers.

3.7 Effect of coffee variety and vermicast rate on Leaf chlorophyll content

The energy of sunlight is first absorbed by plant pigments located in the chloroplasts of leaves. Chlorophyll is a typical pigments that absorb photon energy, consisting primarily of chlorophyll-*a* and an accessory pigment, chlorophyll-*b* (Ying *et al*., 2018). When electrons are excited from their ground state to an excited state through inductive resonance in relation to wavelength, photosynthesis begins (Heber *et al*., 1978). Therefore, biosynthesis and the distribution of substrates in plants are strongly influenced by leaf chlorophyll content (LCC). The analysis of variance (ANOVA) results of the current study show that variety had a highly significant effect ($P \leq 0.05$) on LCC. The observed extremes between the highest and lowest mean chlorophyll contents among the tested coffee varieties were 63.06 and 60.42μmol cm^{-2}, respectively. Variety Kotti was the highest, while the remaining tested varieties produced results that were statistically comparable to one another. In addition to environmental factors (light, temperature, CO_2, and humidity) (EUmRSON, 1929) that affect chlorophyll content, differences in chlorophyll content may also be attributed to genetic differences among the varieties (Ying *et al*., 2018).

Besides variety, vermicast rate also had a significant effect ($P \leq 0.05$) on the LCC of the tested coffee seedlings. The minimum and maximum mean values recorded in the study were 55.07 and 66.88μmol cm^{-2}, respectively. Rate *R*4 was the best, followed by *R*5(64.83) (Table 1). *R*6 showed the least variation, ranging from *R*4 and *R*5 by 17.6% and 15%, respectively. Vermicast is often reported to be rich in nitrogenous nutrients and growth-promoting substances (Nagavallemma *et al*., 2004; Theunissen *et al*., 2010). Nitrogen is involved in several biochemical processes of photosynthesis, including reactions that occur in the chloroplast such as chlorophyll biosynthesis (Theunissen *et al*., 2010). The findings of this study are consistent with those of Atiyeh *et al*. (2000), who reported that using 10% or 20% vermicast mixed with pig solid or food wastes significantly increased chlorophyll content compared with other compost mixtures used in their study.

Table 1. Effect of coffee variety and vermicast rate on Seedling girth, primary branch number, number of leaf and leaf chlorophyll content of 7 months aged coffee seedlings

Factors	Variables			
Variety	SG	PBN	NL	LCC
Kotti	4.45^{A}	2.19^{B}	14.8^{C}	63.06^{A}
74112	4.19^{B}	2.54^{A}	18.93^{A}	60.92^{B}
Fayette	3.90^{C}	1.82^{C}	16.38^{B}	61.34^{B}
74110	3.55^{D}	1.41^{D}	13.66^{D}	60.42^{B}
LSD (P = 0.05)	0.1746	0.2758	0.9867	1.1587
Vermicast Rate				
*R*1	1.34^{E}	3.71^{D}	14.34^{D}	58.57^{E}
*R*2	3.99^{C}	1.72^{D}	15.48^{CD}	60.51^{D}
*R*3	4.15^{BC}	2.12^{C}	16.43^{BC}	62.75^{C}
*R*4	4.35^{B}	3.26^{A}	18.93^{A}	66.88^{A}
*R*5	4.64^{A}	2.53^{B}	17.55^{B}	64.83^{B}
*R*6	3.30^{E}	0.99^{F}	12.93^{E}	55.07^{F}
LSD (P = 0.05)	0.2138	0.3377	1.2085	1.4191
CV %	6.466203	20.63	9.22	2.81

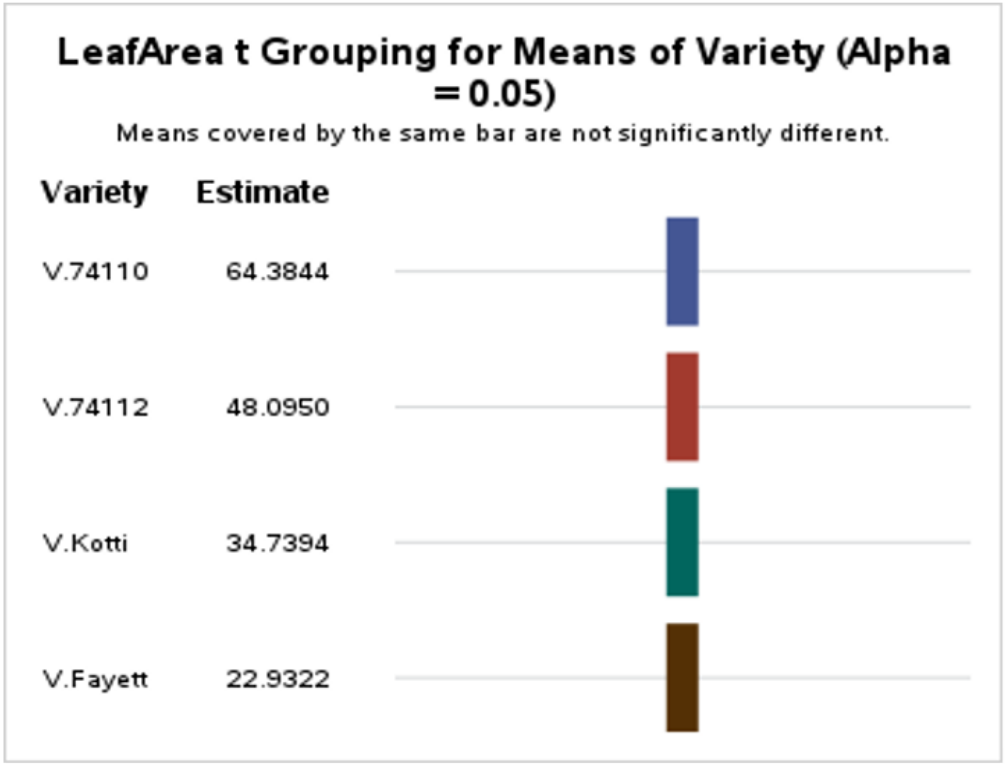
3.8 Effect of coffee variety and vermicast rate on Leaf area (cm^2)

The observed mean value for LA among varieties wide ranged between $66.11cm^2$ and $31.17cm^2$. The highest mean LA recorded from variety Kotti followed by Fayette (51.69) whereas the least mean LA recorded from Variety 74112 (Figure 4A). The genetic variations among varieties, could be a reason for the current variation in mean LA (Gizachew & Hussein 2017; Keiji Jindo, 2020).

This Genotypic variation may also explain the differences in seedling responses to environmental variables in which they grow, and this can provide a good basis for further improvements in the coffee industry (Fikadu *et al*., 2008).

Growth increases of up to 48% were observed in the leaf area of marigold, tomato, green pepper, and cornflower treated with vermicast (Bachman & Metzger, 2008). Leaves are known to function both as a source and a sink—serving as a center for photosynthesis and various physiological processes, as well as for the storage of metabolites such as nitrogen to increase leaf biomass (Adugna *et al*., 2018; Thomas *et al*., 1997).

In this study, *R*5 and *R*4 produced the highest first- and second-ranked mean leaf area (LA) values of 60.10 and 54.49, respectively, followed by *R*3(49.52) (Figure 4B). The increased leaf area observed in largely vermicast-treated seedlings may be due to the availability and concentration of nutrients and growth-promoting hormones that support vegetative growth in coffee seedlings (Arancon *et al*., 2003; Debela & Ayalew, 2018; Edwards *et al*., 1988). The findings of the present study are consistent with those reported by Arancon *et al*. (2005), who established that humic acid extracted from vermicast using the citric acid/alkaline fractionation technique increased the leaf area of tomato. They also reported that $1kg$) of vermicast has the potential to yield $4g$ of humic acid. Furthermore, applying 15^{th} of vermicast increased growth variables, including leaf area (Chandan & Azad 2015)



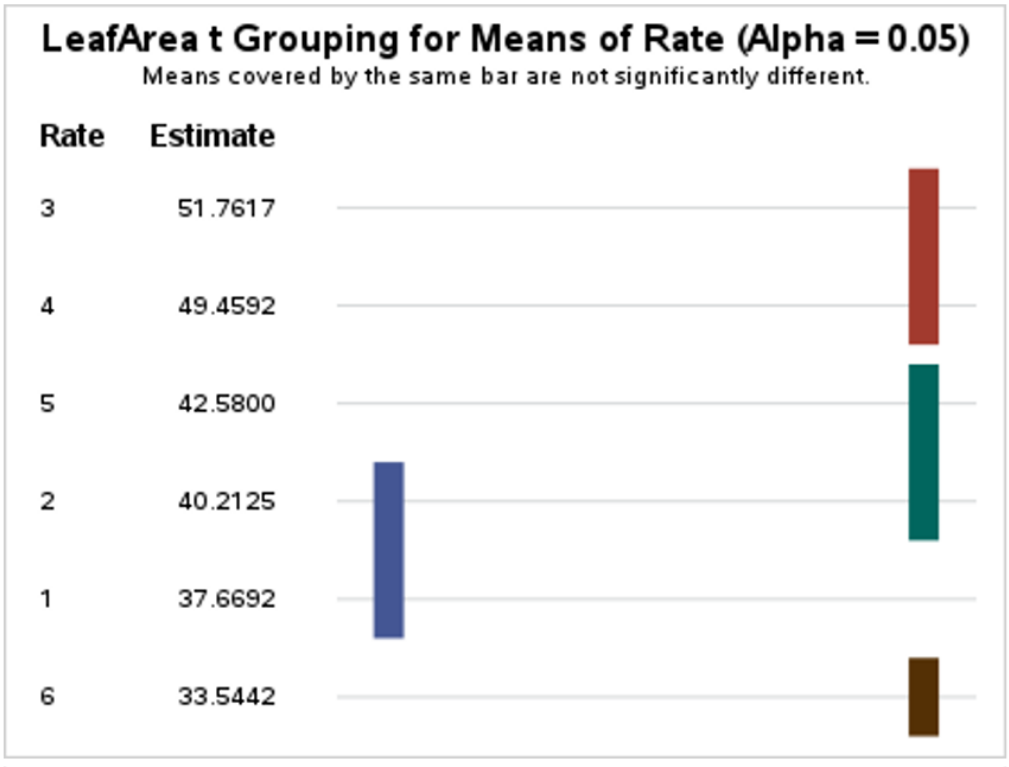


Figure 4. A: Effect of variety on Leaf area of 7 months aged coffee seedlings; **B:** Effect of Vermicast rate on Leaf area of 7 months aged coffee seedlings

3.9 Effect of variety and vermicast rate on Specific Leaf area (cm^2)

Specific leaf area (SLA) measures leaf thickness and is one of the most important traits in its sensitivity to environmental conditions (Amanullah *et al*., 2007). SLA is also a preferred soft plant trait for assessing soil fertility compared with leaf dry matter content (LDMC) (Hodgson *et al*., 2011). Higher SLA generally indicates greater potential productivity and a better relative growth rate (Li *et al*., 2004; Poorter, 2001).

The highest SLA value ($64.38cm^2$) was recorded from variety 74110, followed by $48.09cm^2$ and $30.66cm^2$ for varieties 74112 and Fayette, respectively (Table 2). The possible reason for the higher SLA of variety 74110 may be its greater photosynthetic capacity and improved nutrient-use efficiency, which are genetically regulated (Arancon *et al*., 2003).

Table 2. Effects of coffee variety and vermicast rate on Specific leaf area, primary branch length, dry weight of 7 months aged coffee seedlings

Factors	Variables		
Variety	SLA	PBL	DW
Kotti	34.74^{C}	14.51^{B}	26^{B}
74112	48.09^{B}	16.20^{A}	30.78^{A}
Fayette	22.93^{D}	12.84^{C}	19.05^{C}
74110	64.38^{A}	11.11^{D}	21.72^{C}
LSD (P = 0.05)	2.35	1.62	2.8718
Vermicast Rate			
*R*1	37.67^{C}	10.16^{E}	18.58^{E}
*R*2	40.21^{BC}	12.58^{D}	22.25^{D}
*R*3	51.76^{A}	14.75^{C}	26^{C}
*R*4	49.46^{A}	19.39^{A}	34.58^{A}
*R*5	42.58^{B}	17.35^{B}	30.16^{B}
*R*6	33.54^{D}	7.77^{F}	14.75^{F}
LSD (P = 0.05)	3.33	1.98	3.51
CV %	9.52	17.69	17.55

Among the vermicast rates, the highest and statistically comparable mean SLA values were $51.89cm^2$ and $49.32cm^2$, recorded for *R*3 and *R*4, respectively. In contrast, *R*6 produced the least mean value ($32.96cm^2$) (Table 2). The nutrient content of vermicast is often higher and more readily available than that of other organic nutrient sources used in different studies (Govindapillai *et al*., 2018; Grapelli *et al*., 1985; Indrakumar & Chauhan, 2009). The promotion of plant growth by nutrients and growth-promoting substances such as *N*, *P*, and *K* involves several physiological processes that directly influence plant development. Therefore, the variations observed among treatments may be associated with improved soil physicochemical properties resulting from the increased vermicast rate applied (Arancon *et al*., 2005; Atiyeh *et al*., 2002).

3.10 Effect of coffee variety and vermicast rate on Primary branch length

Primary branches and lateral branches are responsible vegetative parts of the coffee tree that help determine the number of secondary lateral branches and inflorescences (Adriana & Thiago, 2015). The analysis of variance showed that the main effects of variety and vermicast rate were significant ($P \leq 0.01$) for primary branch length (PBL).

For the tested varieties, the mean PBL ranged from 11.11 to $16.21cm$. Variety 74112 produced the highest mean PBL, followed by variety Kotti ($14.51cm$) and Fayette ($12.85cm$) (Table 2). Similarly, the mean PBL values across vermicast rates ranged from 7.77 to $19.40cm$. The highest mean PBL was recorded for seedlings treated with *R*4 (followed by *R*5 at $17.35cm$ and *R*3 at $14.75cm$), whereas the control treatment produced the least mean value (Table 2).

The differences observed among the mean PBL values of the tested varieties and vermicast rates may be due to genetic variability and their interaction with the environment (Fikadu *et al*., 2008; Keiji Jindo, 2020). In addition, improvements in the physicochemical properties of the growing medium, which depend on the level of vermicast applied, may also explain the variation (Debela & Ayalew, 2018). The results of this study are consistent with findings reported by Arancon *et al*. (2005) and Atiyeh *et al*. (2000), who reported that nutrients and humic acid in vermicast improved plant growth in their experiments.

3.11 Effect of variety and vermicast rate on seedling dry weight

Seedling dry weight (DW) influences leaf photosynthetic capacity and the plant's nutrient-using capacity by reflecting nutrient availability and uptake ability of nutrients supplied through vermicast (Arancon *et al*., 2005; Atiyeh *et al*., 2002; Sheng & Hunt, 1991). The highest mean DW (30.78*g*) was recorded for variety 74112, while the lowest (19.05*g*) was recorded for Fayette (Table 2). Variety 74112 was superior to all other tested varieties, possibly due to its efficient nutrient uptake and utilization (Sheng & Hunt, 1991).

With respect to vermicast rate, seedlings treated with *R*4 recorded the highest mean DW (34.58*g*) compared with all other rates (Table 2). Increasing the vermicast rate up to a certain level increased the DW of the coffee seedlings. This may be because vermicast improves the availability and uptake ability of both nutrients and growth regulators (Arancon *et al*., 2003; Arancon *et al*., 2005; Stancheva & Mitova, 2002).

The results of the post-experimental soil analysis further showed that all growing media amended with vermicast had increased total nitrogen (TN), phosphorus (*P*), percent organic carbon (%OC), and organic matter (OM).

3.12 Effect of coffee variety and vermicast rate on seedling biomass

The interaction between vermicast rate and variety had a significant ($P \leq 0.05$) effect on seedling biomass (BM). The highest BM (62.17*g*) recorded from variety Kotti when treated with *R*4 while the least mean value recorded from variety Fayette when treated as control (Figure 5). One of the possible reasons for variation in BM among evaluated seedlings is change in physiology that influenced by growth regulating hormones which impacts are mainly in relation to micro flora and /microbial metabolites that are capable of influencing plant metabolism, growth and development (Edwards *et al*., 1988; Tomati; *et al*., 1988). The level of reaction of seedlings to growth hormones that are contented in vermicast and nutrients such as *N* use efficiency is possibly associated to the genetic condition of the seedlings (Herminia *et al*., 2020). This result is in line with the findings of (Arancon *et al*., 2003; Arancon *et al*., 2005) who reported that Vermicast as organic nutrient source significantly improved seedlings biomass.

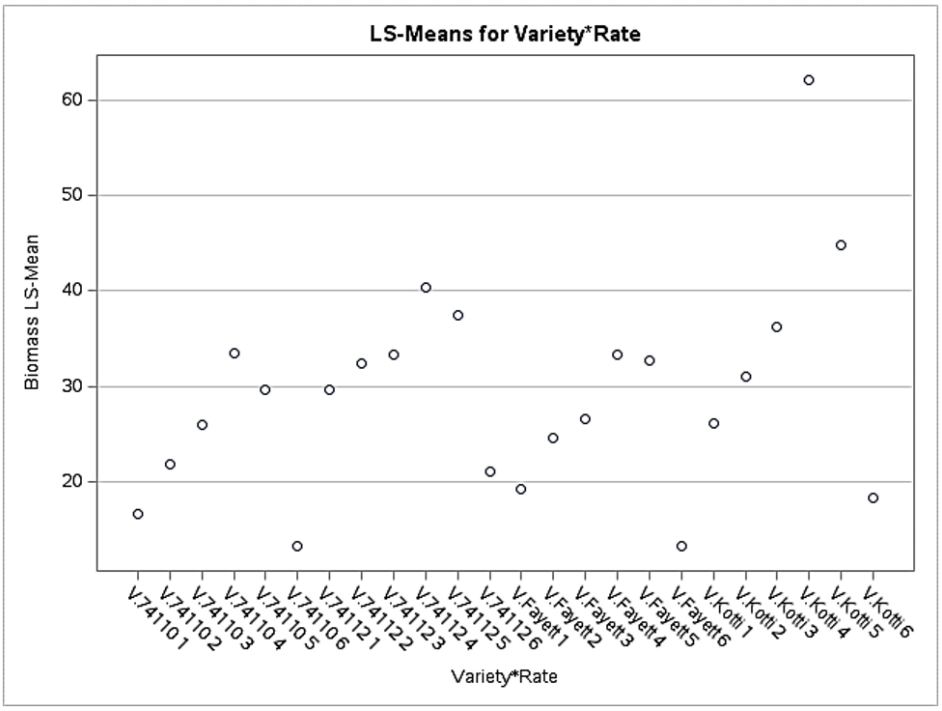


Figure 5. Effect of variety and Vermicast rate on seedling Biomass of 7 months aged coffee seedlings

4 Summary and Conclusion

In this study, twelve variables were evaluated to determine how selected improved coffee varieties responded to different vermicast application rates.

The results of the analysis revealed that both factors significantly affected 50% emergence, number of nodes, and seedling height. Both factors also significantly influenced seedling girth, number of primary branches, number of leaves, leaf chlorophyll content, leaf area, specific leaf area, primary branch length, biomass, and dry weight. However, only vermicast application rate significantly affected days to first emergence, whereas variety had no significant effect.

For most of the evaluated variables, the trends in the graphs showed that increasing the vermicast application rate enhanced coffee seedling growth up to a certain level. Growth, however, began to decline when the application rate exceeded $9.9t\ ha^{-1}$. This reduction may be attributed to vermicast phytohormones reaching concentrations that negatively affect growth processes. The findings are consistent with approximately 95% of previous studies on vermicompost, which reported that vermicast improves plant growth up to an optimum concentration due to its nutrient content, phytohormones, and humic substances (Oyege & Balaji Bhaskar, 2023; Prisa & Jamal, 2025; Rehman *et al*., 2023).

The mechanisms controlling the availability, uptake, and activity of growth-promoting substances in vermicast are not yet fully understood. Further research is therefore needed to identify the types and concentrations of growth hormones present in cow dung vermicast, how they distribute and persist in the growing medium, their uptake by coffee seedlings, and the threshold concentrations beyond which they no longer promote growth.

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Conflicts of Interest

The authors declare no conflict of interest.

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Seasonal and Spatial Variation in Selected Mineral Concentrations of Dairy Cows in the Rift Valley of Ethiopia: A Case Study of Bishoftu and Wonji Shewa

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Abstract

Mineral nutrition is a key determinant of dairy cow productivity and health in Ethiopia's Rift Valley, where seasonal fluctuations and location-specific feeding systems influence mineral availability. Despite its importance, evidence on seasonal and spatial variations in the mineral status of lactating dairy cows in Ethiopia's major dairy-producing areas remains limited. This knowledge gap constrains the development of effective, location-specific mineral supplementation strategies. This study assessed seasonal and spatial variations in calcium, phosphorus, magnesium, copper, iron, zinc, and cobalt in lactating dairy cows and their feeds in the dairy production areas of Bishoftu and Wonji. A total of 80 blood and 78 feed samples collected during the dry and wet seasons were analyzed using standard laboratory procedures. Significant location × season interactions were observed for Ca and Fe ($p < 0.05$). Calcium was marginally adequate, phosphorus remained close to deficiency thresholds, and magnesium and zinc were generally adequate, particularly during the dry season. Copper concentrations were below critical levels and were likely worsened by elevated iron concentrations. Mineral deficiencies were more prevalent in Wonji Shewa (72.5%) than Bishoftu (60%) and were associated with season and physiological status. Lactating cows sampled during the dry season showed the highest deficiency rates. In addition, farmers had limited awareness of mineral deficiency symptoms, especially subclinical reproductive effects. Overall, mineral status varied significantly across locations and seasons, with copper deficiency emerging as the major nutritional constraint. Region- and season-specific mineral supplementation programs, along with farmer education on mineral nutrition and deficiency recognition, should be implemented to improve dairy productivity and cow health.

Keywords/Phrases: Dairy cow nutrition, Trace mineral deficiency, Seasonal dynamics, Spatial variability, Rift Valley

1 Introduction

Mineral nutrition is essential for dairy cow health, reproduction, immune function, and productivity because minerals play key roles in metabolic processes, skeletal development, enzyme activation, and hormonal regulation (McDowell, 2003; Suttle, 2010). In Ethiopia's Rift Valley, where livestock farming supports millions of livelihoods, mineral deficiencies —especially calcium (*Ca*), phosphorus (*P*), copper (*Cu*), and cobalt (*Co*) —pose major challenges to sustainable dairy production. The region's diverse agro-ecological zones and distinct wet and dry seasons influence the mineral composition of soils and forages, thereby affecting the mineral intake of cattle. Variations in soil characteristics, rainfall patterns, vegetation types, and forage species across agro-ecological zones can change the concentration, bioavailability, and uptake of minerals by plants, ultimately influencing the mineral status of grazing animals (McDowell & Arthington, 2005; Underwood & Suttle, 1999).

Studies have shown that Ethiopian forages often contain inadequate levels of essential minerals, particularly during the dry season when pasture quality and biomass availability decline (Gizachew & Smit, 2012). Seasonal rainfall fluctuations not only affect forage quantity but also influence nutrient cycling, plant maturity, and mineral accumulation in pasture species. During prolonged dry periods, reduced forage growth and increased lignification may decrease mineral concentrations and mineral bioavailability to ruminants (Suttle, 2010; McDowell, 2003). As a result, serum mineral levels in dairy cows from areas such as East Shoa are frequently below critical thresholds, leading to suboptimal health, reduced milk production, impaired fertility, weakened immune responses, and increased susceptibility to metabolic disorders (Wondewsen *et al*., 2020).

Despite the recognized importance of mineral nutrition, detailed information on the seasonal and spatial variation of mineral concentrations in dairy cows —particularly comparisons between lactating and dry cows—remains limited in Ethiopia's Rift Valley (Gizachew & Smit, 2012). Physiological differences associated with lactation, including increased mineral demands for milk synthesis, may further affect mineral status and worsen deficiencies when dietary mineral supply is inadequate (Suttle, 2010). This knowledge gap limits the development of evidence-based, region-specific, and season-specific mineral supplementation strategies to improve animal health and productivity (Khakurel *et al*., 2021).

Therefore, this study investigates the macro- and micro-mineral status of dairy cows in Bishoftu and Wonji Shewa across different seasons and physiological stages. The study aims to generate baseline information that can guide targeted nutritional interventions and improve dairy production efficiency in Ethiopia's Rift Valley.

2 Materials and Methods

2.1 Study Area

The study was conducted in Bishoftu and Wonji Shewa, two districts in the East Shewa Zone of the Oromia Region, Ethiopia, located in the central Rift Valley. Bishoftu lies at an elevation of approximately 1,850 – 1,900m above sea level and has a subtropical highland climate with bimodal rainfall patterns and a rapidly expanding peri-urban dairy sector. Wonji Shewa is located at an elevation of 1,500 – 1,700m above sea level, has a semi-humid climate, and benefits from irrigation-based agriculture associated with the Awash River basin. Both areas have distinct agro-ecological characteristics and support mixed crop–livestock production systems (Abebe *et al*., 2020; CSA, 2022).

2.2 Study Population

The study included a total of 80 dairy cows, comprising 40 from Bishoftu and 40 from Wonji Shewa. In each district, 20 lactating and 20 dry cows were selected to ensure balanced representation of physiological status. Cows were chosen based on age (2 – 5 years) and good general health, which was confirmed through clinical examination by a veterinarian. These selection criteria were used to minimize potential confounding effects related to age and health status.

2.3 Blood Sample Collection

Blood samples were aseptically collected from the jugular vein of each cow using sterile vacutainer tubes according to standard veterinary procedures (Radostits *et al*., 2007). For plasma mineral analysis, blood was drawn into tubes containing ethylenediaminetetraacetic acid (EDTA) as an anticoagulant. Immediately after collection, samples were labeled and transported to the laboratory in an ice-cooled container. Upon arrival, plasma samples were stored at -20°C until laboratory analysis.

2.4 Plasma Mineral Estimation

Plasma concentrations of calcium (Ca), phosphorus (P), magnesium (Mg), copper (Cu), iron (Fe), zinc (Zn), and cobalt (Co) were determined using Atomic Absorption Spectrophotometry (AAS) following standard analytical procedures (Underwood and Suttle, 1999). Prior to analysis, plasma samples were thawed and prepared according to laboratory protocols. Calibration standards and quality-control samples were included throughout the analytical procedure.

The concentration of each mineral was calculated using the following equation:

Mineral concentration ($mg\ L^{-1}$) =

$$\frac{(Absorbance \times Standard\,Concentration) \times Dilution\,Factor}{Sample\,Volume}$$

Where:

- Absorbance = instrument reading of the sample
- Standard Concentration = concentration of calibration standard
- Dilution Factor = dilution applied during sample preparation
- Sample Volume = volume of plasma analyzed

2.5 Trace mineral concentrations

Trace mineral concentrations of copper (Cu), iron (Fe), zinc (Zn), and cobalt (Co) were determined using an ECIL 4141 Atomic Absorption Spectrophotometer (Electronics Corporation of India Ltd., India) equipped with a double-beam optical system operating over a wavelength range of 190 – 900nm (Reddy *et al.*, 2021). Each mineral was analyzed using its corresponding hollow cathode lamp with an air–acetylene flame. Calibration curves were prepared using at least three standard solutions. Mineral concentrations were recorded in parts per million (ppm) using a computer-integrated data acquisition system. To minimize cross-contamination, the instrument was flushed with distilled water for at least 10 minutes between successive samples.

2.6 Feed Sample Collection Preparation

A total of 78 feed samples, consisting of 30 roughage, 36 concentrate, and 12 non-conventional feed samples, were collected from dairy farms in Bishoftu and Wonji Shewa during both wet and dry seasons using random sampling procedures. Approximately 500 g of each sample was collected according to established protocols (FAO, 2013; NRC, 2001). Samples were placed in labelled polyethylene bags and transported to the laboratory for analysis. Upon arrival, samples were air-dried, ground to pass through a 1mm sieve, and stored in airtight containers until analysis (AOAC, 2005). Macro-minerals (Ca, P, and Mg) and trace minerals (Cu, Fe, Zn, and Co) were determined using Atomic Absorption Spectrophotometry following AOAC (2005) procedures.

2.7 Digestion of Plasma Samples

Before mineral determination, plasma samples were digested using a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 4:1 ratio following standard wet-digestion procedures (Gent *et al.*, 2011). Samples were heated gradually until a clear solution was obtained, indicating complete oxidation of the organic matter. The digested samples were then cooled and diluted to a known volume with deionized water prior to mineral analysis.

Statistical Analysis

Data were analyzed using two-way analysis of variance (ANOVA) to evaluate the effects of season, district, and their interaction on mineral concentrations. The model included fixed effects for season, district, and the season × district interaction. Post-hoc pairwise comparisons were performed using Tukey's Honest Significant Difference (HSD) test to identify significant differences between group means. Statistical analyses were conducted using SPSS version 26.0, and significance was determined at $p < 0.05$ (Field, 2013).

2.8 Ethical Clearance

This study was conducted in accordance with ethical standards and procedures for animal research. Ethical clearance was obtained from the Addis Ababa University of Debrezeit Veterinary and Agricultural College (protocol approval number VM/ERC/07/11/018). Verbal consent was also obtained from all participating dairy farm owners and personnel prior to sample collection. No invasive procedures were performed on the animals; all sampling and handling were carried out with minimal stress to ensure animal welfare.

3 Results and Discussions

3.1 Prevalence Patterns by Risk Factors

The overall prevalence of mineral deficiency was 60% in cows from Bishoftu and 72.5% in cows from Wonji Shewa (Table 1). A significant association was observed between location and mineral status ($\chi^2 = 10.20$, $p < 0.005$). This difference may reflect variations in soil mineral content, feeding practices, and forage availability. Cows in Wonji Shewa were

more likely to experience deficiencies, possibly due to differences in grazing or mineral supplementation. In a study conducted in the East Shoa Zone, Oromia Region, phosphorus (*P*) deficiency was reported in both lactating and dry cows, which was attributed to low *P* levels in native pastures (Wondewsen *et al*., 2020). This finding supports the notion that regional soil and forage characteristics influence cattle mineral status.

Table 1. Prevalence of the condition under study by origin, physiological state, body condition and season

Variables	Categories	No sampled	Positive	Prevalence %	χ^2	P-value
Origin	Bisheftu	40	24	60.00	10.20	0.005
	Wonji Shewa	40	29	72.50		
	Total	80	53	66.30		
Physiological state	Dry cow	40	22	55.00	25.48	0.000
	Lactating cow	40	31	77.50		
	Total	80	53	25.48		
Body condition	Good	43	26	60.50	0.00	0.517
	Medium	21	14	66.70		
	Poor	16	13	81.30		
	Total	80	53	66.30		
Season	Wet	40	20	50.00	2.48	0.000
	Dry	40	33	82.50		
	Total	80	53	66.30		

3.2 Physiological State

Lactating cows had a much higher rate of mineral deficiency (77.5%) compared to dry cows (55%). As a result, there was a strong association between physiological state and mineral status ($\chi^2 = 25.48$, $p < 0.001$). Notably, this finding highlight that lactating cows are more prone to mineral depletion. This suggests that the increased metabolic demands for milk production place additional stress on mineral reserves. Consistent with this, Kumar *et al*. (2018) also reported higher requirements for calcium, phosphorus, and magnesium during lactation. However, Mummed *et al*. (2023) found sufficient magnesium levels in both lactating and dry cows in the same area. This indicates that not all minerals are equally influenced by physiological state, and some may be buffered despite increased demands.

Mineral deficiency was most common in cows with poor body condition (81.3%), followed by those with medium (66.7%) and good condition (60.5%). Overall, this pattern suggests greater nutritional stress in animals with low body reserves. However, the differences were not statistically significant ($\chi^2 = 0.00$, $p > 0.05$). This implies that, although body condition may influence mineral status, the effect may not always be detectable statistically. Similarly, Mummed *et al*. (2023) reported irregular mineral levels in cows with poor body condition in nutrient-deficient environments. In contrast to earlier studies that found a strong association between body condition and mineral balance, the present findings did not confirm such a relationship, possibly due to variations in local feed quality and herd management practices.

3.3 Seasonal Variation

Season had a significant impact on mineral deficiency ($\chi^2 = 29.45$, $p < 0.001$), with a higher prevalence in the dry season (82.5%) than in the wet season (66.3%). This suggests reduced pasture quality and lower forage mineral content during dry periods. Consistent with previous studies, Ndoti *et al*. (2020) reported severe mineral and protein deficiencies during the dry season in Senegal, particularly

in lactating cows. In addition, Kumar *et al*. (2018) observed marked seasonal variation in feed mineral content in Ethiopian dairy systems. Unlike earlier research that focused mainly on protein, the present study emphasizes the need for seasonal mineral supplementation.

3.4 Dairy Owners' Knowledge of Mineral Deficiency

This study assessed the seasonal occurrence of mineral deficiencies and related symptoms in dairy cows in the two locations —Bishoftu and Wonji Shewa (Table 2).

Table 2. Dairy owners' knowledge of seasonal occurrence of mineral deficiency in the study area

Variables	Bishoftu (n = 40)	Wonji Shewa (n = 40)	Overall Total (N = 80)	Chi-Square (χ^2)
Dairy owners' knowledge about Mineral Deficiency (%)				
Yes	24 (60.0)	26 (65.0)	50 (62.5)	0.23, p > 0.05
No	16 (40.0)	14 (35.0)	30 (37.5)	
Dairy owners' opinion about seasonal occurrence of Mineral Deficiency (%)				
Dry Season	28 (70.0)	29 (72.5)	57 (71.3)	0.04, p > 0.05
Wet Season	1 (2.5)	1 (2.5)	2 (2.5)	
Both Seasons	2 (5.0)	1 (2.5)	3 (3.8)	
No Idea	9 (22.5)	9 (22.5)	18 (22.5)	
Total	40(100)	40(100)	80(100)	

Mineral deficiencies were most common during the dry season; therefore, fodder scarcity likely reduced mineral availability, particularly for lactating cows (Ndoti *et al*., 2020). This highlights the role of seasonal changes in driving mineral imbalances through reduced pasture quality and forage intake. Dairy farmers in both areas showed comparable awareness of mineral deficiencies, consistent with Alemayehu *et al*. (2012), who reported that access to extension services —rather than location —shapes knowledge. In contrast, studies from northern Ethiopia found that cultural beliefs strongly influenced awareness (Gizaw *et al*., 2019). Hence, the relatively uniform knowledge observed in the present study is likely associated with stronger veterinary outreach in these urban-adjacent regions.

3.5 Recognition of Mineral Deficiency Symptoms

The study assessed dairy owners' recognition of clinical signs of mineral deficiency (Table 3) and revealed overall low awareness, with no significant difference between Bishoftu and Wonji Shewa (χ^2 = 0.16, p > 0.05). Milk fever was the most recognized symptom, reported by 22.5% of farmers in Bishoftu and 20.0% in Wonji Shewa, likely reflecting its acute and visible presentation (McDowell, 2003). Notably, awareness of subclinical signs was poor; farmers mostly identified severe symptoms such as recumbency or milk loss, consistent with Girma (2016). However, unlike Suttle (2010), who reported that emaciation, lameness, and soil licking were relatively commonly recognized, the present study found significantly lower acknowledgment of soil licking (3.8%) and emaciation (1.3%).

Knowledge of reproductive signs (e.g., silent heat and delayed puberty) was also limited, suggesting that subclinical effects on fertility often go unnoticed, which may contribute to reproductive inefficiencies. The present study, consistent with Alemayehu *et al*. (2012), indicates that mineral deficiencies are frequently overlooked because their symptoms overlap with other conditions. In contrast to studies from highland areas, where lameness and emaciation were commonly reported (Tadesse *et al*., 2017), this study observed fewer such cases, possibly due to differences in management practices or breed susceptibility.

Table 3. Recognition of mineral deficiency symptoms among dairy owners in the study area

Variables	Bishoftu (n = 40)	Wonji Shewa (n = 40)	Overall Total (N = 80)	
Dairy owners observation about mineral deficiency symptoms (%)				
Loss of Hair Coat	4 (10.0)	3 (7.5)	7 (8.8)	$\chi^2 = 0.16$, $p > 0.05$
Licking of Human Urine	5 (12.5)	6 (15.0)	11 (13.8)	
Lameness	1 (2.5)	1 (2.5)	2 (2.5)	
Soil Licking	1 (2.5)	2 (5.0)	3 (3.8)	
Delayed Onset of Puberty	0 (0.0)	1 (2.5)	1 (1.3)	
Silent Heat	1 (2.5)	1 (2.5)	2 (2.5)	
Irregular Estrous	1 (2.5)	2 (5.0)	3 (3.8)	
Failure of Estrous	1 (2.5)	1 (2.5)	2 (2.5)	
Long Period of Calving Interval	1 (2.5)	1 (2.5)	2 (2.5)	
Embryonic Death	1 (2.5)	0 (0.0)	1 (1.3)	
Increased Incidence of Dystocia	1 (2.5)	1 (2.5)	2 (2.5)	
Retention of Placenta	1 (2.5)	1 (2.5)	2 (2.5)	
Blindness in Newborns	0 (0.0)	1 (2.5)	1 (1.3)	
Emaciation	0 (0.0)	1 (2.5)	1 (1.3)	
Milk Fever Incidence	9 (22.5)	8 (20.0)	17 (21.3)	
Milk Quality and Quantity Affected	3 (7.5)	3 (7.5)	6 (7.5)	

Notably, this study determined the concentrations of key macro-minerals (*Ca*, *P*, and *Mg* in $g\ L^{-1}$) and micro-minerals (*Cu*, *Fe*, *Zn*, and *Co* in $mg\ L^{-1}$) in lactating and dry cows across wet and dry seasons in the peri-urban dairy regions of Bishoftu and Wonji Shewa in the East Shoa Rift Valley, Ethiopia (Table 4). The results were compared with established critical thresholds for dairy cattle and interpreted in relation to recent literature, considering seasonal, spatial, and physiological variations that may contribute to mineral imbalances and affect dairy health and productivity.

Table 4. Mean concentrations of macro ($g\ L^{-1}$) and micro-minerals ($mg\ L^{-1}$) in the blood serum of lactating and dry dairy cows across dry and wet seasons in the study area

Physiological status	Study area	Macro Minerals ($g\ L^{-1}$)			Micro Minerals ($mg\ L^{-1}$)			
		Ca	*P*	*Mg*	*Cu*	*Fe*	*Zn*	*Co*
Lactating n=40	Wonji shewa	0.085	0.040	0.155	0.590	2.281	1.980^{b}	ND
	Bisheftu	0.080	0.040	0.135	0.675	2.590	1.890^{c}	ND
Mean		0.083	0.040	0.145	0.633	2.436	1.935	
Dry Cow n=40	Wonji shewa	0.090	0.040	0.135	0.521	2.481	2.406^{a}	ND
	Bisheftu	0.085	0.045	0.125	0.641	2.420	2.170^{ab}	ND
Mean		0.086	0.043	0.130	0.581	2.451	2.288	
Overall Mean		0.085	0.042	0.138	0.607	2.443	2.112	
SE		0.002	0.0011	0.006	0.0013	0.5103	0.118	
Interaction effect								
Phy × study area		0.8833	0.7645	0.1827	0.6745	0.0758	0.8369	
Critical level		$< 0.08^{g}$	< 0.04	< 0.012	< 0.65	< 1.0	< 0.6	ND

Values are means per location and season.
"ND" indicates not detected. Superscript letters within columns denote statistically significant differences at $p < 0.05$.
Critical levels indicate the minimum concentrations required to avoid deficiency according to McDowell (2003) and Puls (1994).

3.6 Blood Serum Mineral Concentrations

Plasma calcium concentrations ranged from 0.075g L^{-1} in Wonji Shewa during the dry season to 0.085g L^{-1} in Bishoftu, with an overall mean of 0.080g L^{-1} (Table 5). A significant location $\times$ season interaction ($p < 0.05$) indicated that both spatial and seasonal factors influenced calcium status. Calcium levels in Bishoftu were slightly above the critical threshold of 0.08g L^{-1}, suggesting adequate status, consistent with Tadesse *et al.* (2017), who reported similar values (0.081g L^{-1}) in well-managed herds in Ethiopia's central highlands. In contrast to Nzioka *et al.* (2020), who reported stable calcium concentrations throughout the year due to consistent supplementation in southern Ethiopia, this study showed seasonal declines, particularly in Wonji Shewa during the dry season, suggesting uneven supplementation practices across regions.

In Kenya and Uganda, calcium concentrations in herds fed fortified diets were reported to exceed 0.09g L^{-1} (Fall-Toure *et al.*, 2014). Conversely, calcium levels in Wonji Shewa during the dry season fell below the threshold, which may be linked to poorer forage quality in lowland, semi-arid areas. Likewise, although Mekonnen *et al.* (2022) reported no seasonal variation in calcium under intensive feeding, the present findings suggest that reliance on natural forage and extensive grazing may predispose cows to marginal deficiencies. These results align with Goff (2008), who associated forage mineral decline with prolonged dry periods in Ethiopian rangelands, and with Chibsa and Gure (2020), who reported that suboptimal calcium during early lactation can impair productivity and reproduction.

Plasma phosphorus concentrations ranged from 0.035 to 0.040g L^{-1}, with a mean of 0.0395g L^{-1}, which was slightly but significantly below the critical threshold of 0.04g L^{-1}", indicating a marginal deficiency. No significant interaction between study area and season was detected ($p > 0.05$), suggesting phosphorus levels were relatively consistent across locations and seasons. Phosphorus is important for energy metabolism, bone development, and reproduction. The borderline deficiency observed —particularly in Bishoftu during the dry season —may be related to reduced forage phosphorus due to declining soil fertility and increased plant maturity. These findings are consistent with Tadesse *et al.* (2023), who reported suboptimal phosphorus in central Ethiopian dairy herds linked to reduced reproductive performance and milk yield, and with Abay *et al.* (2021), who associated soil phosphorus limitations and low-quality forage with mineral imbalances, especially during dry seasons. By comparison, Crnkic and Hodzic (2012) in South Africa reported more severe phosphorus deficiency in cattle grazing phosphorus-depleted pastures; however, the present study found only a marginal shortfall. Similarly, while Orjales *et al.* (2018) reported lower phosphorus in indigenous Zebu cows near parturition in South Africa, the current study showed no significant difference between lactating and dry cows, suggesting a broadly uniform deficiency across physiological states. The lack of seasonal variation may indicate sustained year-round dietary insufficiency regardless of environmental conditions or lactation stage.

Plasma magnesium concentrations ranged from 0.105 to 0.170g L^{-1} (mean: 0.151g L^{-1}), well above the deficiency threshold of 0.012g L^{-1}. No significant season $\times$ location interaction was observed ($p > 0.05$), indicating stable magnesium status across sites and seasons. All values fell within physiologically adequate ranges, suggesting sufficient intake and absorption under current management. These results agree with Suttle (2010), who reported elevated magnesium levels in Rift Valley livestock, likely due to mineral-rich volcanic soils and groundwater. Magnesium also plays a key role in preventing hypomagnesemia (grass tetany) (Musa *et al.*, 2022). Nevertheless, high potassium or nitrogen in lush pastures may reduce magnesium absorption without necessarily lowering plasma concentrations (Suttle, 2010), so continued monitoring—particularly after pasture flushes following rains—is warranted.

Plasma copper concentrations ranged from 0.570 to 0.610mg L^{-1} (mean: 0.588mg L^{-1}), consistently below the critical threshold of 0.65mg L^{-1} for dairy cattle. No significant season $\times$ location interaction was found ($p > 0.05$), indicating uniformly low copper status across sites. Although the deficiency was marginal, these concentrations suggest the possibility of subclinical copper deficiency. Copper is essential for hemoglobin synthesis, immune function, reproduction, and antioxidant defense, and requirements

increase in lactating cows due to greater metabolic activity (Suttle, 2010). The marginal deficiency may be aggravated by mineral antagonism, particularly the elevated iron levels observed in this study, which can impair copper absorption. Similar subclinical copper deficiencies have been reported in central Ethiopia (Orjales *et al*., 2018) and Kenya (Musa *et al*., 2022).

Plasma iron concentrations ranged from 2.281$mg\ L^{-1}$ (dry season, Wonji Shewa) to 3.381$mg\ L^{-1}$ (wet season, Wonji Shewa), with a mean of 2.784$mg\ L^{-1}$, which was well above the critical threshold of 1.0$mg\ L^{-1}$ for dairy cattle. A significant location × season interaction was reported ($p > 0.05$). Although iron toxicity is uncommon in cattle, excessive iron can interfere with the absorption of other trace elements, particularly copper (*Cu*) and zinc (*Zn*). Therefore, this antagonism may have contributed to the marginal copper and zinc deficiencies observed, despite adequate or near-threshold intakes.

Plasma zinc concentrations ranged from 2.041 to 2.280$mg\ L^{-1}$ (mean: 2.163$mg\ L^{-1}$), which was well above the critical threshold of 0.6$mg\ L^{-1}$. No significant interaction between season and location was detected ($p > 0.05$), indicating consistent zinc status across districts and seasons. These adequate levels are encouraging because zinc supports immune function, wound healing, and reproduction. However, even with adequate plasma zinc concentrations, zinc bioavailability may still be reduced by elevated iron and the marginal copper levels observed in this study.

3.7 Seasonal Mineral Concentrations

3.7.1 Macro Mineral Concentrations

Calcium concentrations ranged from 0.075 to 0.08$g\ L^{-1}$, with the highest level in Bishoftu during the dry season (0.085$g\ L^{-1}$) and the lowest in Wonji Shewa (0.075$g\ L^{-1}$). The mean *Ca* level (0.080$g\ L^{-1}$) was slightly but significantly above the critical threshold (< 0.08$g\ L^{-1}$). A significant interaction between location and season ($p > 0.05$; SEM = 0.0037) indicates that calcium availability is influenced by both geographic and seasonal factors. These findings are in line with Mekonnen *et al*. (2022), who highlighted the role of soil type and rainfall in regional mineral variation. However, in contrast to the current study, Crnkic and Hodzic (2021) reported no seasonal fluctuation in plasma calcium, likely due to consistent mineral supplementation.

Phosphorus levels ranged from 0.035 to 0.040$g\ L^{-1}$, with a mean of 0.0395$g\ L^{-1}$, notably just below the critical threshold (< 0.04$g\ L^{-1}$). No significant interaction between season and location was observed ($p > 0.05$; SEM = 0.0012), therefore indicating stable *P* status across sites and seasons. These marginal values are consistent with Garamu (2019). who reported borderline *P* levels in Ethiopian smallholder dairy systems. The lack of seasonal variation contrasts with Suttle, N.F. (2010), who noted higher *P* levels during the wet season due to improved forage quality.

3.7.2 Micro Mineral Concentrations

Copper concentrations ranged from 0.570 to 0.610$mg\ L^{-1}$, just below the critical threshold (< 0.65$mg\ L^{-1}$), with no significant location-season interaction ($p > 0.05$; SEM = 0.0025). Although marginally deficient, these values align with those reported by NRC (2001) for tropical grazing systems. The absence of seasonal variation mirrors findings from Miller *et al*. (2021), therefore suggesting stable *Cu* levels in mixed feeding systems.

Iron concentrations showed the most pronounced variability. Levels ranged from 2.281$mg\ L^{-1}$ at Wanji Shewa (dry season) to 3.381$mg\ L^{-1}$ at Wanji Shewa (wet season), with an overall mean of 2.784$mg\ L^{-1}$. The interaction between season and location was significant ($p < 0.05$), indicating that *Fe* content was strongly influenced by both factors. Importantly, all values were well above the critical requirement of 1.0$mg\ L^{-1}$, highlighting that drinking water is a major *Fe* source in both study areas. However, excessive *Fe* can impair *Cu* and *Zn* absorption (Crnkic & Hodzic, 2012), potentially leading to secondary deficiencies even when absolute dietary levels appear adequate. The elevated wet-season values may reflect soil erosion and runoff during rains, as previously reported in volcanic soil areas of East Africa (Musa *et al*., 2022).

Zinc concentrations varied between 2.041 – 2.280$mg\ L^{-1}$, with an overall mean of 2.163$mg\ L^{-1}$. No significant differences were observed across seasons or

study areas ($p > 0.05$). All values were well above the critical requirement of $0.6 mg\ L^{-1}$, indicating that water makes a meaningful contribution to *Zn* nutrition. Adequate *Zn* is crucial for reproductive performance and immune competence (Garamu, 2019). However, given the high *Fe* levels in these samples, *Zn* bioavailability may be partially reduced through mineral antagonism (Miller *et al*., 2021).

Table 5. Mean concentrations of macro-minerals ($g\ L^{-1}$) and micro-minerals ($mg\ L^{-1}$) in the blood serum of lactating and dry dairy cows across dry and wet seasons in study area

Study area	Season	Macro Minerals ($g\ L^{-1}$)			Micro Minerals ($mg\ L^{-1}$)			
		Ca	*P*	*Mg*	*Cu*	*Fe*	*Zn*	*Co*
Bishoftu	Dry	0.085^{a}	0.035	0.170	0.570	2.681^{ab}	2.041	ND
	Wet	0.080^{ab}	0.040	0.105	0.580	2.690^{ab}	2.190	ND
Mean		0.083	0.041	0.138	0.575	2.686^{ab}	2.116	
Wanji Shewa	Dry	0.075^{b}	0.040	0.170	0.610	2.281^{b}	2.140	ND
	Wet	0.080^{ab}	0.035	0.155	0.592	3.381^{a}	2.280	ND
Mean		0.076	0.038	0.163	0.601	2.883	2.210	
Overall Mean		0.080	0.0395	0.151	0.588	2.784	2.163	
SE		0.0037	0.0012	0.0036	0.0025	0.1123	0.1301	
Interaction effect								
Study area × Season		0.0182	0.6974	0.0836	0.914	0.0199	0.2387	
Critical level		$< 0.08^{g}$	< 0.04	< 0.012	< 0.65	< 1.0	< 0.6	ND

Values are presented as means per location and season.
Superscripts indicate statistically significant differences within minerals ($p < 0.05$). "ND" denotes minerals not detected.
Critical levels represent deficiency thresholds based on Puls (1994) and McDowell (2003).

Table 6 shows that roughages had the highest calcium (*Ca*) content, averaging 0.63% during the wet season, which was significantly greater than concentrates (0.36%) and non-conventional feeds (0.54%) ($p < 0.0001$). Both feed type and the feed × season interaction significantly affected *Ca* levels ($p < 0.0001$), whereas season alone had no significant effect ($p > 0.05$). Roughage *Ca* ranged from 0.61% (dry season) to 0.63% (wet season), while concentrates and non-conventional feeds had lower, relatively stable values.

These results align with previous studies indicating that green and leguminous forages generally contain more *Ca*, likely because their deeper root systems access mineral-rich soil (Suttle, 2010; Gizaw *et al*., 2019). Overall, roughages appear to be the main contributors to dietary calcium in this production system, whereas diets relying primarily on concentrates or non-conventional feeds may increase the risk of marginal *Ca* deficiency.

The seasonal increase in roughage *Ca* corresponds with higher nutrient uptake during wetter periods, as reported in the Ethiopian highlands by (Kumar, 2018; Ndoti *et al*., 2020). Unlike studies that attribute *Ca* variation primarily to season alone, the present study emphasizes the importance of the feed × season interaction, indicating that mineral uptake is jointly influenced by both factors. The lower *Ca* concentration in concentrates highlights the need for dietary supplementation, particularly for lactating cows, to reduce the risk of hypocalcaemia. Non-conventional feeds contained moderate *Ca* levels; however, their variability may limit their reliability as a consistent *Ca* source. Overall, these findings are consistent with existing literature, while underscoring site-specific and seasonal dynamics in feed mineral composition.

Table 6. Seasonal variations in macro- and micro-mineral concentrations (mean ± SEM) in different feed types (roughages, concentrates, and non-conventional feeds) sampled in study area

Feed type	Season	Macro minerals (%)			Micro minerals ($mg\ kg^{-1}$)			
		Ca	*P*	*Mg*	*Cu*	*Fe*	*Zn*	*Co*
Roughage n=30	Dry	0.61^{a}	0.50^{ab}	0.86^{a}	8.47	103.25	32.46^{b}	ND
	Wet	0.63^{a}	0.64^{b}	1.09^{a}	8.49	115.26	33.41^{b}	ND
Concentration n=36	Dry	0.35^{b}	0.59^{ab}	0.45^{b}	7.71	106.24	38.38^{ab}	ND
	Wet	0.38^{b}	0.64^{b}	0.58^{b}	8.01	122.15	41.46^{a}	ND
Non-conventional n=12	Dry	0.50^{ab}	0.65^{b}	0.34^{b}	7.54	95.27	30.15^{ab}	ND
	Wet	0.59^{a}	0.89^{a}	0.54^{b}	7.68	106.13	33.00^{b}	ND
Overall mean (n= 78)		0.51	0.65	0.807	7.98	108.05	34.81	
SEM		0.034	0.033	0.047	0.264	6.543	1.139	
P-value								
Feed type		0.0001	0.0003	0.0001	0.079	0.408	0.0001	
Season		0.702	0.754	0.0009	0.084	0.094	0.857	
Feed × Season		0.0001	0.0001	0.0001	0.124	0.357	0.0001	

Different superscripts (a, b) within columns indicate significant differences ($p < 0.05$) between means; ND = Not Detected.

Phosphorus (*P*) concentrations were highest in non-conventional feeds (0.89%) during the wet season, followed by roughages and concentrates, both at approximately 0.64%. *P* varied significantly with feed type ($p < 0.001$) and the feed × season interaction ($p < 0.001$), but not with season alone ($p > 0.05$; SEM = 0.033). These results are consistent with findings from East Shoa (Ndoti *et al.*, 2020), where non-conventional feeds —such as brewery residues and agro-industrial by-products —contained elevated *P* due to mineral enrichment during processing. Although roughages and concentrates showed moderate and similar *P* levels, the higher *P* content in non-conventional feeds during the wet season highlights their potential value as *P* supplements. The observed seasonal increase also agrees with (Ndoti *et al.*, 2020), who reported enhanced plant phosphorus uptake under moist and biologically active conditions. While some studies report larger seasonal variation in traditional forages, this study demonstrates that both feed type and seasonal dynamics strongly shape *P* availability (Underwood & Suttle, 1999). Consequently, incorporating non-conventional feeds may help mitigate *P* deficiencies; however, supplementation should be balanced to avoid mineral imbalances.

Magnesium (*Mg*) concentrations were highest in roughages (1.09%) during the wet season, followed by concentrates (0.58%) and non-conventional feeds (0.54%). *Mg* levels were significantly affected by feed type ($p < 0.0001$), season ($p < 0.001$), and their interaction ($p < 0.0001$; SEM = 0.047). Roughages consistently contributed more *Mg*, particularly during the wet season, likely due to improved soil solubility and greater plant uptake. These findings are consistent with (Field, 2013; Gizaw *et al.*, 2019), who reported higher *Mg* in leguminous and green forages, especially during rainy periods (Ndoti *et al.*, 2020). Concentrates, which are largely grain- and oilseed meal-based, are typically lower in *Mg*, whereas non-conventional feeds provide moderate *Mg* depending on their composition. Therefore, even with lower *Mg* than roughages, non-conventional feeds can still support adequate intake when used within balanced rations. Magnesium is essential for neuromuscular function, enzyme activity, and calcium regulation; thus, *Mg* deficiency can contribute to grass tetany, particularly in early spring or during dry seasons (Suttle, 2010). The high *Mg* levels in roughages during the wet season suggest a lower risk, but supplementation may still be necessary during dry periods or under high-potassium conditions that inhibit *Mg* absorption.

3.8 Micro-Minerals in Dairy Feeds

Copper (*Cu*) concentrations were highest in roughages ($8.49 mg\ kg^{-1}$) during the wet season, followed by concentrates ($8.01 mg\ kg^{-1}$) and non-conventional feeds ($7.68 mg\ kg^{-1}$). Differences among feed types ($p < 0.001$), across seasons ($p = 0.084$), and for the feed × season interaction ($p > 0.05$) were not statistically significant (SEM = 0.264). Overall, *Cu* levels remained close to the minimum dietary requirement of $8 – 10 mg\ kg^{-1}$ for ruminants. The slightly higher *Cu* in roughages is consistent with findings from mineral-rich or volcanic soils (Field, 2013; Gizaw *et al*., 2019). Seasonal increases may also reflect greater microbial activity and improved solubility in moist soils (Ndoti *et al*., 2020). However, *Cu* bioavailability can be reduced by antagonistic minerals, particularly iron, which was also elevated in these feeds and is known to interfere with *Cu* absorption (Crnkic & Hodzic, 2012). Although differences were statistically non-significant, the marginal *Cu* levels in concentrates and non-conventional feeds agree with previous reports from the Ethiopian highlands (Chibsa & Gure, 2020; Tadesse *et al*., 2023).

Iron (*Fe*) concentrations peaked in concentrates ($122.15 mg\ kg^{-1}$) during the wet season, followed by roughages ($115.26 mg\ kg^{-1}$) and non-conventional feeds ($106.13 mg\ kg^{-1}$). Feed type ($p > 0.05$), season ($p < 0.05$), and their interaction ($p > 0.05$) showed no significant overall effects (SEM = 6.543). Nonetheless, all feeds exceeded the ruminant *Fe* requirement of $50 mg\ kg^{-1}$ DM (Abule *et al*., 2021). Elevated *Fe* in concentrates may be attributed to the presence of iron-rich ingredients (e.g., wheat bran or molasses) or potential contamination during processing (Hu *et al*., 2021). In addition, volcanic soils and mineral-rich water can contribute to elevated *Fe* in forages (Orjales *et al*., 2018). While *Fe* toxicity is uncommon, excessive *Fe* can inhibit the absorption of *Cu* and *Zn*, thereby increasing the risk of secondary deficiencies (Crnkic & Hodzic, 2012). The wet-season increase in *Fe* likely reflects erosion and runoff processes, as well as the use of mineral-laden water during feed mixing, as also reported by Orjales *et al*. (2021).

Zinc (*Zn*) concentrations were highest in concentrates ($41.46 mg\ kg^{-1}$), followed by roughages ($33.41 mg\ kg^{-1}$) and non-conventional feeds ($33.00 mg\ kg^{-1}$). *Zn* varied significantly with feed type ($p < 0.0001$) and the feed × season interaction ($p < 0.0001$), but not with season alone ($p > 0.05$; SEM = 1.139). All feeds exceeded the critical *Zn* requirement ($30 – 40 mg\ kg^{-1}$ DM) (Abule *et al*., 2021). Higher *Zn* in concentrates likely reflects the inclusion of mineral premixes and more consistent diet formulation (NRC, 2001). The seasonal rise in *Zn* —particularly in concentrates —may be related to improved feed quality and supplementation during the wet season. Despite overall adequate *Zn* concentrations, bioavailability may be reduced by elevated dietary *Fe* and *Ca*, both of which were present in excess (Crnkic & Hodzic, 2012). Therefore, *Zn* uptake may be influenced by seasonal factors, plant maturity, and soil characteristics such as p*H* and organic matter (Miller *et al*., 2021). Even in forage-based systems, seasonal *Zn* limitations may occur; hence, routine mineral profiling and targeted supplementation are recommended to support reproductive and immune functions.

4 Conclusion and Recommendations

This study demonstrated variations in the mineral status of dairy cows across locations, seasons, and physiological states in Bishoftu and Wonji Shewa, Ethiopia. The results showed that mineral deficiencies were more prevalent in Wonji Shewa, particularly during the dry season and among lactating cows. These findings indicate that location, season, and physiological status are key risk factors influencing mineral balance. Among the minerals assessed, calcium and phosphorus were marginally deficient, especially during the dry season. In contrast, copper concentrations remained consistently below critical levels across the study areas. Magnesium and zinc were generally within adequate ranges. Cobalt was not detected in most samples, whereas iron concentrations exceeded critical requirements, suggesting a potential risk of antagonistic interactions that may reduce the bioavailability of copper and zinc. The study also showed that seasonal changes in feed mineral composition contribute to variations in animal mineral status, emphasizing the importance of feed quality for sustaining optimal productivity and animal health. These mineral imbalances may negatively affect milk production, re-

productive performance, immune competence, and overall herd productivity, particularly in lactating and high-producing dairy cows.

Based on these findings, location- and season-specific mineral supplementation programs are recommended, with particular emphasis on calcium, phosphorus, copper, and cobalt. Routine monitoring of mineral status in both dairy cows and feeds should be strengthened to enable early detection and correction of deficiencies. In addition, dairy producers should receive support through targeted extension services and farmer training programs focused on mineral nutrition, appropriate supplementation practices, and the recognition of health problems associated with mineral deficiencies. Such interventions will contribute to improved dairy productivity, better animal health, and greater sustainability of dairy production systems in the Ethiopian Rift Valley.

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Data availability statement

The data that support the findings of this study are available from the corresponding author on reasonable request.

Declaration of interests' statement

The authors declare no conflict of interest

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Determinants of agroforestry-based smallholder farmers' choices of adaptation to climate change and variability in southern Rift Valley Escarpments of Ethiopia

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Abstract

Climate change poses substantial risks to agriculture and food security in Ethiopia, particularly among smallholder farmers in the southern Rift Valley. This study investigates the key determinants influencing adaptation choices among farmers in the Gedeo Zone. Employing an explanatory research design, the study integrates both quantitative and qualitative methodologies. A structured questionnaire was administered to a sample of 384 households across three districts, complemented by focus group discussions and key informant interviews to enrich qualitative insights. Quantitative data were analyzed using descriptive statistics and a propensity score matching (PSM) framework, combined with a binary logistic regression model to estimate treatment effects and control for confounding variables. Concurrently, qualitative data were examined through thematic analysis, where emergent patterns and recurrent concepts were systematically identified, categorized, and synthesized into coherent thematic constructs. Findings reveal that the majority of farmers in Kochere (65.67%) and Wonago (62.16%) districts do not adopt agroforestry, whereas Yirgachefe district exhibits a higher adoption rate (51.08%). Factors significantly influencing agroforestry-based adaptation choices include household age, gender, farm size, access to basic services, participation in local institutions, and wealth and asset status. The study demonstrates that agroforestry substantially enhances climate resilience, with 59.75% of adopters reporting improved resilience compared to only 5.78% of non-adopters (t-value = 14.32). This proven the synergy between agroforestry and climate resilience firmly establishes it as a strategic pillar of sustainable rural development. The results underscore the urgent need for targeted policy interventions and community-driven strategies to promote agroforestry, thereby fostering resilience, sustainability, and food security in the Gedeo Zone.

Keywords/Phrases: Adaptation, Agroforestry, Climate change, Ethiopia, Gedeo Zone

1 Introduction

Ethiopia is among the most climate change-vulnerable countries, experiencing rising temperatures, erratic rainfall, and increasingly severe weather events. These changes have significantly impacted agricultural productivity, leading to food insecurity and poverty (Abebe *et al*., 2018; Asnake, 2021; Deressa *et al*., 2019). In the southern Rift Valley escarpments, smallholder farmers, heavily reliant on rain-fed agriculture, are particularly at risk. Their vulnerability underscores the urgent need for effective adaptation strategies (Abebe *et al*., 2018; Mekonnen *et al*., 2016). Agroforestry, a practice integrating trees into farming systems, offers a promising means to enhance resilience to climate challenges (FAO, 2019). By combining agricultural and forestry practices, agroforestry mitigates the impacts of climate variability while supporting livelihoods (Regassa *et al*., 2020).

Agroforestry has deep historical roots in Ethiopia, originating approximately 7000 years ago and evolving into a prominent farming practice in most regions except the semiarid lowlands (Sileshi, 2016). In areas such as Gedeo, traditional agroforestry features dense arrangements of trees, shrubs, and crops, ensuring continuous plant cover. This system provides immediate agricultural and social benefits, with climate mitigation as a valuable secondary effect (Ogle *et al*., 2014). Such practices enhance crop yields (Amare, 2017) and are regarded as exemplary land-use models (Gebrehiwot *et al*., 2014).

Climate change adaptation is critical for farming communities such as those in the Gedeo Zone, as it enhances their resilience against the adverse effects of climate variability (Fissha, *et al*., 2019). Agricultural practices that incorporate adaptive strategies can significantly improve food security and livelihoods by mitigating risks associated with unpredictable weather patterns (Lobell *et al*., 2014). Additionally, diversifying crops and improving water management are essential for maintaining productivity in the face of changing climatic conditions (Mastrorillo *et al*., 2016). Community engagement in adaptation strategies fosters local knowledge and resource utilization, which is vital for sustainable development (Kassam *et al*., 2020). Ultimately, effective adaptation not only supports agricultural sustainability but also preserves cultural heritage and community identity in the face of environmental challenges (Adger *et al*., 2018).

While agroforestry's potential for climate change adaptation is widely recognized (Adimassu *et al*., 2014; Debele *et al*., 2018; Regassa *et al*., 2020), critical research gaps persist. Limited studies have explored factors influencing smallholder farmers' adaptation decisions in the south-eastern Rift Valley escarpments (Gebrehiwot *et al*., 2014; Muluneh *et al*., 2015). Existing research often generalizes agricultural adaptation strategies, overlooking the unique dynamics of agroforestry systems in this specific context. For instance, Kessler (2014) emphasize the need for focused studies on adaptation strategies tailored to agroforestry, especially in distinct regions like the northern Ethiopian highlands.

Moreover, the lack of studies addressing spatial and temporal variations in crop diversity within agroforestry systems limits our understanding of adaptation strategies (Deressa *et al*., 2019; Hagos *et al*., 2011; Tesfaye, 2014). Tesfaye and Bongers (2014) put the need for further investigation on determinants agroforestry-based smallholder farmers' adaptation decisions in response to climate change and variability. These gaps highlight the necessity of localized research accounting for ecological and socio-economic variations in the south-eastern Rift Valley (Deressa *et al*., 2019; Gebreegziabher *et al*., 2010).

This study seeks to address these gaps by investigating the determinants of smallholder farmers' agroforestry adaptation decisions in the Gedeo Zone. Employing Propensity Score Matching (PSM) to account for selection bias and unobserved confounders, this research provides robust insights into agroforestry's role in enhancing resilience to climate change. By filling these critical gaps, the study contributes valuable knowledge to the discourse on sustainable land management and adaptation strategies for vulnerable farming communities in Ethiopia.

2 Materials and Methods

2.1 Description of study area

This study was conducted in selected districts within Gedeo Zone, located in Southern Ethiopia Regional State. Geographically, the Zone lies north of the equator, between 5°53'N to 6° 27'N latitude and from 38° 8' to 38° 30'east longitude (Negash, 2010). It is located along on the main highway connecting Addis Ababa near the Kenya border, 365 kilometers south of Ethiopia's capital city Addis Ababa. Slope gradient reaches up to 70% in some areas and almost 50% of the landscape is steep, with slope gradient above 10 % (Mesele, 2011; MCTA, 2020). The majority of the soil type in the area is Nitosol (Abiyot, 2013), typically made up of volcanic rocks. The Zone has three agro-ecological zones whose mid altitude agro-ecology occupies the largest area (62.2%) followed by high land (37.1%) and low altitude (0.7%) (Bogale, 2007). The study districts, namely Kochere, Yirgachefe and Wonago are among the districts in the Gedeo Zone Southern Ethiopia regional state (Figure 1). Kochere district is found between 6°09' N latitude and 38°'16'E longitude. Elevations range from 1,500 to 3,100 meters above sea level (masl), and the study area comprises two agro-

climate zones: Dega (with elevations between 2,300 and 3,700 masl, accounting for 26%) and Weyna Dega (ranging from 1,500 to 2,300 masl, constituting 74%) according to Yibrah (2014). The average annual temperature falls between 25°C and 31°C, while the annual rainfall ranges from 1,000 to 1,200 millimeters, as reported by Adugna (1998).

Yirgachefe district is located between 6°09' and 6°32' N and 38°08' and 38°32' E, with an altitudinal range of 1501–2500 masl (Negash 2007). The annual rainfall ranges between 1200 and 1800mm, with a bimodal distribution, and the mean annual temperature varies from 15°C to 20°C (Asnake, 2021). Wonago district is found between 6°20' E and 6°32' E, and 38°14' N and 38°24' N, with an undulated type of landscape and an altitude ranging from 1601 to 2875 masl. The district receives rainfall of 800 to 1400mm per annum and annual temperatures ranging from 11°C to 29°C (Negash 2007). All study districts are categorized as mid and highlands based on elevation, with a range of 1500–3700 masl.

2.2 Study site selection

The three research districts, namely Kochere, Yirgachefe, and Wonago, were purposefully selected to characterize the agroforestry-based adaptation options to climate change and variability in these districts. This selection was driven by the high prevalence of indigenous agroforestry practices in the coffee-producing belt of the Zone. From each district, three kebeles (the smallest administration unit in Ethiopia) were randomly chosen: two from the midlands and one from the highlands. In total, the study included nine kebeles of which six are from the midlands and three are from the Highlands. Accordingly, Jeldo and Anchabi from the midland, as well as Gololicha kebele from the highland of the Kochere district (symbolizing Woina dega and dega,

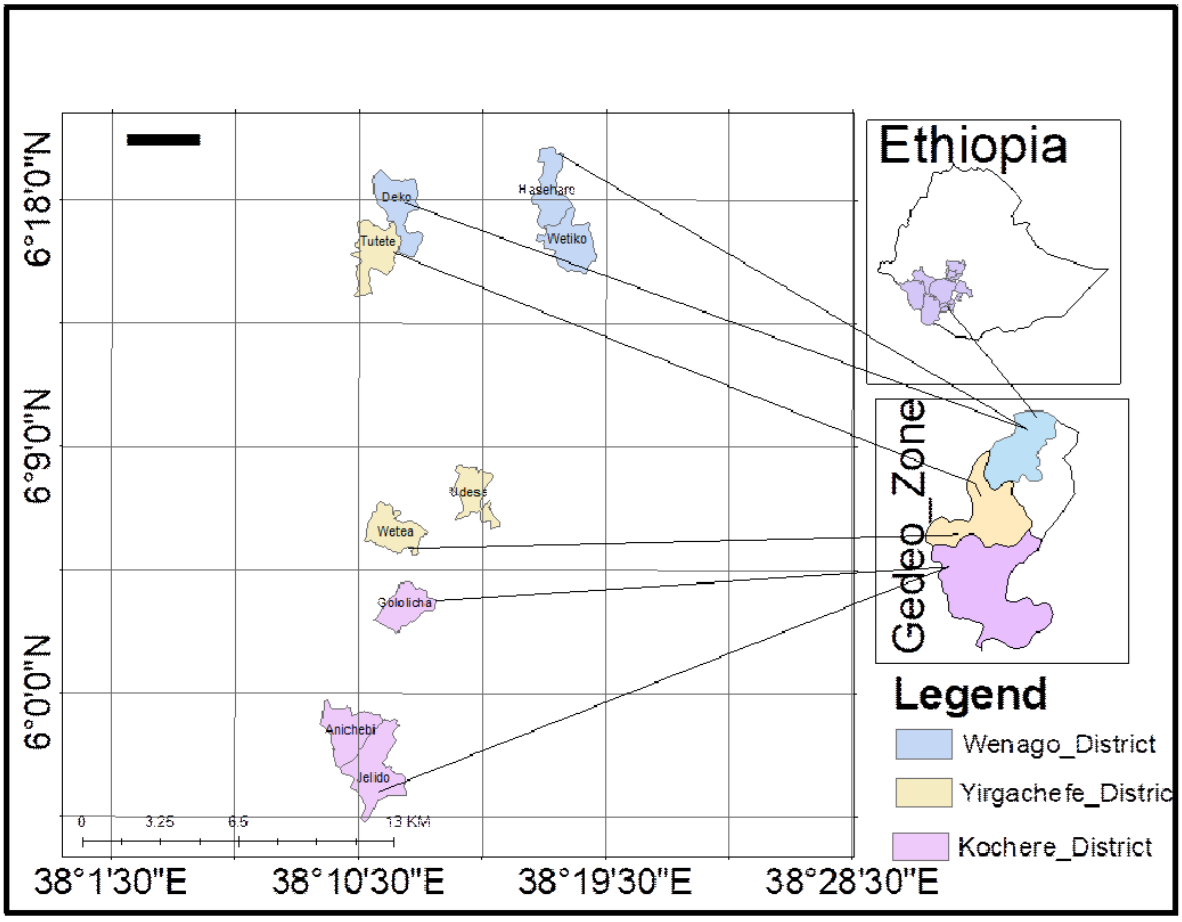


Figure 1. Location map of study area

respectively), were chosen. Similarly, in the Yirgachefe district, Tutit and Wote (from the midlands) and Udesa kebele (from Woina dega) were included. Likewise, Deko and Hase Haro (from the midlands) and Wotiko kebele from the Woina dega were randomly selected in the Wonago district, with the expectation that agroforestry-based adaptation options would vary across different kebeles in diverse agro-ecologies.

2.3 Research Design

For the purpose of this study, an explanatory research design was employed to explain how independent variables (determinant factors) determine dependent variable (farmer's agroforestry adaptation status).

2.4 Research Approach

To achieve the study's objective, the researcher used a mixed-methods approach, combining quantitative and qualitative methods. Quantitative data were gathered through structured surveys of smallholder farmers, covering demographics, farm practices, agroforestry adoption, climate change perceptions, and adaptation strategies. Qualitative data were collected via in-depth interviews and focus group discussions as a subset of the surveyed farmers. This comprehensive approach provided a deeper understanding of the factors influencing farmers' adaptation choices.

2.5 Data type and sources

This study used both primary and secondary data. Primary data were gathered through household surveys, key informant interviews, and focus group discussions. Secondary data were collected from government reports, academic journals, published and unpublished materials (theses, dissertations), and websites. By triangulating these diverse sources, the study aims to comprehensively understand the factors influencing smallholder agroforestry farmers' adaptation decisions to climate change and variability in the Gedeo Zone, southern Ethiopia.

2.6 Sampling techniques and sample size determination

Multiple-stage stratified sampling methods were used in the study. First, districts were selected due to high climatic change and variability. Second, the district is grouped by their agro-ecology (strata) on the basis of their elevation, where 1500–2300 masl is categorized as midland and above 2300 masl is categorized as high land. Third, kebeles were chosen from each agro-ecology stratum for data uniformity, and finally, households were randomly selected from selected kebeles on the basis of their wealth status using proportional sampling. The wealth status of the sample households were stratified into three groups based on well-defined local criteria for the study area using key informants: rich locally known as (dureessa), medium (oddicha), and poor (hiyeessa). Proportional sampling was then employed to take sample sizes from each wealth category. This is because smallholder farmers' agroforestry-based adaptation options vary in reference to demographic and socioeconomic factors.

The sample size of sampled households was determined following Yemane (1967) sampling techniques as follows:

$$n = \frac{N}{1+N(e)^2} = \frac{9662}{1+9662(0.05)^2} = \frac{9662}{1+9662(0.0025)} = \frac{9662}{25.155}$$

$$= 384$$

Where n, N, and e represent the sample size (number of respondents), total number of households and level of precision (allowable error, 5%), respectively.

For sample size allocation at kebele level, the proportional allocation formula was used as:

$$n_i = \frac{N_i * n}{N}$$

Where; n_i = the sample size proportion of each kebele, N_i = the population proportion in the stratum (kebeles), n = the sample size of the districts, and N = the total population of the districts.

Table 1. Total household and sample size of the study area

Name of Districts	Name of Kebeles	Total Households	Sampled Households	
			Freq.	Percentage
Kochere	Jeldo	1073	43	11.19
	Anchabi	1024	41	10.79
	Gololcha	1253	50	13.02
Yirgachefe	Tutit	801	32	8.33
	Wote	970	39	10.15
	Udesa	1014	40	10.41
Wonago	Deko	1002	40	10.41
	Hase Haro	880	35	9.11
	Wotiko	1645	64	16.66
Total	9	9662	384	100

2.7 Data collection methods

The survey, conducted from August to October 2022, utilized structured questionnaires complemented by focus group discussions (FGDs), key informant interviews (KIs), and observations to gather both quantitative and qualitative data, enabling deeper insights and triangulation. Regassa *et al*. (2020) provided a framework for examining smallholder farmers' climate change adaptation strategies in Ethiopia.

Structured Questionnaire: Quantitative data were collected using a questionnaire initially designed in English, translated into the 'Gede'uffa' language for fieldwork clarity, and later retranslated into English for analysis.

Focus Group Discussions (FGDs): Separate discussions with elders, youth, and women in each Kebele (8–12 participants per group) explored topics such as climate change perceptions, agroforestry adaptation strategies, and determining factors. The sessions were organized around three themes, focusing on farmers' insights into agroforestry practices, their intentions to adopt such practices, crop diversity, and climate adaptation strategies. Each discussion lasted about 90 minutes, during which detailed written notes were taken to document the participants' contributions, as audio recordings were not used.

Key Informant Interviews (KIs): Using snowball sampling (Martin, 1995), 45 key informants (five per Kebele) were selected. Semi-structured interviews focused on climate change prediction, information sources, indigenous tree planting, and a determinant of adaptation was used. Input from district specialists and development agents ensured diversity among respondents. This comprehensive approach provided rich data to analyze smallholder farmers' adaptation decisions to climate change in the Gedeo Zone.

2.8 Methods of data analysis

The study primarily utilized quantitative methods, with descriptive statistics (percentages, means, Chi-squares) analyzed using STATA software version 15.0. A Logit model was also employed for deeper analysis. Qualitative data, obtained through interviews and focus group discussions, were analyzed using thematic analysis involving identification, categorization, and synthesis of recurring idea into coherent thematic constructs. This approach facilitated the recognition of patterns in farmers' adaptation decision. The study references Regassa *et al*. (2020) for smallholder farmers' adaptation strategies and the Food and Agriculture Organization of the United Nations (2019) for insights into agroforestry-based climate resilience in Ethiopia.

2.9 Model specification

Propensity Score Matching (PSM)

Propensity Score Matching (PSM) is a method used to estimate the causal effect of a treatment (in this case, farmers' participation in agroforestry) on an outcome variable (climate resilience). The propensity score is defined as the probability of receiving the treatment given a set of observed covariates. The mathematical derivation of the specified variables was as follows:

Step 1: Define the Model

We define the treatment variable Y_i (FAFAS$_i$) as follows:

Y_i = 1 if farmer i adopts agroforestry; 0 otherwise.

The outcome variable CR (climate resilience) is also binary:

CR$_i$ = 1 if farmer i has climate resilience; 0 otherwise.

Step 2: Logistic Regression for Propensity Score Estimation

The propensity score $e(X_i)$ is modeled using a logistic regression, where X_i represents the vector of independent variables:

$e(X_i) = \mathrm{P}(Y_i = 1 \mid X_i) = 1 \,/\, 1 + e^{(-\eta_i)}$

Where, η_i is given by:
$\eta_i = \beta_\circ + \beta_1$ Agehh$_i$ + β_2 Sexhh$_i$ + β_3 Mshh$_i$ + β_4 Hhfz$_i$ + β_5 Educ$_i$ + β_6 Farmsize$_i$ + β_7 Accessbs$_i$ + β_8 Accessmkt$_i$ + β_9 Agroecology$_i$ + β_{10} Foodsec$_i$ + β_{11} Hhinco$_i$ + β_{12} Participation$_i$ + β_{13} Wealth$_i$

Here, X_i = Agehh, Sexhh, Mshh, Hhfz, Educ, Farmsize, Accessbs, Accessmkt, Agroecology, Foodsec, Hhinco, Participation, Wealth.

Step 3: Estimation of Propensity Scores

Using maximum likelihood estimation, we fit the logistic regression model to obtain the coefficients β_i. The estimated propensity score is calculated as follows:

Fit the Logistic Regression: This yields estimates for $\beta_\circ$, β_1, ... β_{11}.

Calculate Propensity Scores: For each observation, compute: $e(X_i) = \mathrm{P}(Y_i = 1 \mid X_i) = 1 \,/\, 1 + e^{(-\eta_1)}$

Step 4: Matching Process

Following the estimation of the propensity scores, treated units defined as farmers who adopted agroforestry were matched with control units, comprising farmers who did not adopt agroforestry. This matching procedure aims to balance covariates across groups, thereby minimizing selection bias and enabling a more robust estimation of treatment effects.

Table 2. Description of variables and its expected and observed output (sign)

Variables name	Variables code	Measurement	Exp. Sign	Obtained Sign
Dependent variable				
Farmer's agroforestry adaptation options status to climate changes and variability	$FAFAS_i$	Binary (FAFAS i =1 if farmers adapt agroforestry as adaptation options to climate changes and variability, 0 otherwise)		
Outcome variable				
Climate resilience due to agroforestry adaptation	CR	Binary (1 if yes, 0 otherwise)		
Independent variables				
Age of the household heads	Agehh	Continuous categorical variable (0= 20-30 years, 1= 31-40 years, 2 = 41-50 years, 3= 51 - 60, 4= above 60 years old)	+	+
Sex of the household heads	Sexhh	Binary (1 = male, 0 = female)	+	+
Marital status of the household heads	Mshh	Binary with many choice (1 if married, 0 otherwise, 2 if single, 0 otherwise, 3 if divorced, 0 otherwise and 4 if widowed, 0 otherwise)	-	-
Family size of the households	Hhfz	Continuous categorical variable (1 if 6-10, 0 otherwise, 2 if above 10, 0 otherwise)	+	-
Education level of the household heads	Educ	Binary with many choice (1 if illiterate, 0 otherwise, 2 if primary, 0 otherwise; 3 if secondary, 0 otherwise, 4 if certificate, 0 otherwise and 5 if diploma and above, 0 otherwise	+	+
Farm size in ha owned by the households	Farmsize	Binary with many choice (1 if Poor (HH have 0 to 0.5ha), 0 otherwise, 2 if Medium (HH have 0.51 to 1.6 ha), 0 otherwise; 3 if rich (HH have above 1.6 ha), 0 otherwise)	+	+
Access to basic services	Accessbs	Binary (1 if households get adequate access to basic services, 0 otherwise)	+	+
Access to market	Accessmkt	Binary (1 if households have adequate access to market services, 0 otherwise)	+	+
Agro ecology	Agroecology	Binary with many choice (1 if low (if elevation 0 to 1500), 0 otherwise, 2 if Medium (if elevation 1500 to 2300), 0 otherwise; 3 if High (if elevation 2300 to 3100), 0 otherwise)	+	-
Food security status of the households	Foodsec	Binary (1 if hhs are food secured (gets 2100kcal/day/person, 0 otherwise)	+	+
Income of the household heads	Hhinco	Binary (1 if Poor (adult HH earns less than 1.9$), 0 otherwise, 2 if rich (adult HH earns more than 1.9$, 0 otherwise)	+	+
Participation status of the farmers in local institutions	Participation	Binary (1 if the household members have participation in local institution, 0 otherwise)	+	+
Wealth category of the households	Wealth	Binary with many choice (1 if Poor (Hiyeessa), 0 otherwise, 2 if Medium (Oddicha), 0 otherwise; 3 if rich (Dureessa), 0 otherwise).	+	+

3 RESULTS

3.1 Farmer's agroforestry adaptation status to climate changes and variability characteristics

Farmers' agroforestry adaptation status to climate change and variability is detailed in Table 3, along with the characteristics of their districts.

The results presented in Table 3 highlight the adaptation status of farmers to agroforestry practices in Kochere, Wonago, and Yirgachefe districts of the Gedeo Zone. Overall, 58.59% of farmers reported non-adaptation, while 41.41% had adopted agroforestry practices. In Kochere, 65.67% (88 farmers) did not adopt agroforestry, while 34.33% (46 farmers) had adapted. In Wonago, 62.16% (69 farmers) reported non-adaptation, and 37.84% (42 farmers) adopted, suggesting slightly better initiatives or support. Conversely, Yirgachefe recorded a higher adaptation rate, with 51.08% (71 individuals) adopting agroforestry and 48.92% (68 individuals) remaining non-adopters.

Table 3. Summary of farmer's agroforestry adaptation status to climate changes and variability characteristics

Farmer's adaptation status	Districts							
	Kochere		Wonago		Yirgachefe		Mean	
	Freq	%age	Freq	%age	Freq	%age	Freq	%age
Farmers did not adapt agroforestry adaptation options	88	65.67	69	62.16	68	48.92	225	58.59
Farmers adapt agroforestry adaptation options	46	34.33	42	37.84	71	51.08	159	41.41
Total	134	34.9	111	28.91	139	36.2	384	100

3.2 Demographic and socioeconomic characteristic of agroforestry adopters and non-adopters

Table 4 characterizes the demographic and socioeconomic factors that determine farmers' agroforestry adaptation to climate change and variability. It also statistically tests the significance of these factors using p-values.

The demographic and socioeconomic characteristics of agroforestry adopters and non-adopters in the Kochere, Wonago, and Yirgachefe districts reveal key factors influencing adoption decisions.

Age: Adoption is highest among the 51-60 age group (28.93%) and lowest in the 20-30 group (11.95%), likely due to greater experience and resources among older farmers. Non-adoption is highest in the 31-40 group (35.5%), reflecting challenges like economic pressures or lack of awareness. Age significantly influences adoption (chi-square = 0.001).

Gender: The majority of adopters (85.53%) and non-adopters (93.78%) are male, aligning with traditional roles in agriculture. Gender dynamics have a marginally significant impact (p = 0.05). Engaging women in agroforestry could boost adoption (Agarwal, 2010).

Family Size and Marital Status: Both factors show no significant impact on adoption decisions (p = 0.751 and p = 0.347, respectively), with similar distributions across adopters and non-adopters.

Education Level: Illiteracy is more prevalent among non-adopters (71.56%) than adopters (25.16%), with education significantly influencing adoption (chi-square = 0.02). Educational programs can enhance adoption among less educated populations (Mekonnen *et al*., 2020).

Farm Size: Larger farms (>1.6ha) are more common among adopters, while smaller farms (0-0.5 ha) dominate among non-adopters. Farm size strongly affects adoption (chi-square = 21.74, p < 0.001).

Access to Basic Services: Adopters (64.15%) report better service access compared to non-adopters (73.33% inadequate). Improved service access significantly supports adoption (chi-square = 4.01, p = 0.045).

Agroecology: Both groups predominantly reside in midland areas, with no significant differences in agro-ecological zones (p = 0.647).

Food Security Status: Non-adopters face higher food insecurity (74.67%) than adopters (25.16%). While food security correlates with adoption, it lacks statistical significance (p = 0.082).

Table 4. Demographic and socioeconomic characteristics of agroforestry adopters and non-adopters in South-eastern Ethiopia

Variables	Variable categories	Agroforestry adaptation decision							
		Adopters		Non-adopters		Total			
		Freq.	%	Freq.	%	Freq.	%	χ^2	p-value
Age	20-30	19	11.95	28	12.44		12.24	23.48	0.001
	31-40	33	20.75	80	35.50		29.02		
	41-50	35	22.01	78	34.67	114	29.87		
	51-60	46	28.93	37	16.44	83	21.61		
	I>60	26	16.35	2	0.89	28	7.29		
	Total	159	41.41	225	58.59	384	100		
Gender	Male	136	85.53	221	93.78	347	90.36	3.79	0.05
	Female	23	14.47	14	6.22	37	9.64		
	Total	159	41.41	225	58.59	384	100		
Family size	1-5	21	13.21	44	19.56	65	16.93	0.1	0.751
	6-10	56	35.22	67	29.78	123	32.03		
	>10	82	51.57	114	50.67	196	51.04		
	Total	159	41.41	225	58.59	384	100		
Marital status	Married	104	65.41	174	77.33	278	72.4	2.79	0.347
	Single	24	15.09	9	4.00	33	8.59		
	Divorced	12	7.55	14	6.22	26	6.77		
	Widowed	19	11.95	28	12.44	47	12.24		
	Total	159	41.41	225	58.59	384	100		
Education level	Illiterate	40	25.16	161	71.56	201	52.34	0.02	0.885
	Primary	58	36.48	46	20.44	104	27.08		
	Secondary	41	25.79	16	7.11	57	14.84		
	Certificate	20	12.58	2	0.89	22	5.73		
	Total	159	41.41	225	58.59	384	100		
Farm size, ha	0-0.5	40	25.16	170	75.56	210	54.69	21.74	<0.00
	0.51-1.6	41	25.79	41	18.22	82	21.35		
	> 1.6	78	49.06	14	6.22	92	23.96		
	Total	159	41.41	225	58.59	384	100		
Access to basic service	Inadequate	57	35.85	165	73.33	222	57.81	4.01	0.045
	Adequate	102	64.15	60	26.67	162	42.19		
	Total	159	41.41	225	58.59	384	100		
Agroecology	Mid land	128	80.50	161	71.56	289	75.26	0.21	0.647
	High land	31	19.50	64	28.44	95	24.74		
	Total	159	41.41	225	58.59	384	100		
Food security status	Insecure	40	25.16	168	74.67	208	54.17	3.02	0.082
	Secure	119	74.84	157	25.33	176	45.83		
	Total	159	41.41	225	58.59	384	100		
Participation in local institutions	Not participated	41	25.79	173	76.89	214	55.73	5.82	0.015
	Participated	118	74.21	52	23.11	170	44.27		
	Total	159	41.41	225	58.59	384	100		
Wealth and asset status	Poor	54	33.96	134	59.56	188	48.96	5.05	0.024
	Medium	76	47.00	75	33.3	151	39.32		
	Rich	29	18.40	16	7.11	45	11.72		
	Total	159	41.41	225	58.59	384	100		

Participation in Local Institutions: Adopters (74.21%) show greater engagement in local institutions than non-adopters (23.11%), significantly enhancing access to agroforestry resources (chi-square = 5.82, p = 0.015).

Wealth and Asset Status: Wealthier farmers are more likely to adopt agroforestry, with financial constraints limiting non-adopters (59.56%). Wealth significantly influences adoption (chi-square = 5.05, p = 0.024).

These insights highlight critical factors shaping agroforestry adoption and point to targeted interventions to support sustainable practices.

3.3 Descriptive Results of Outcome Variables: Climate Resilience Due to Farmers' Agroforestry Adaptation

In Table 5, climate resilience resulting from farmers' agroforestry adaptation is characterized and statistically analysed using t-tests and p-values to determine the level of significance.

Table 5. Summary of climate resilience due to farmer's agroforestry adaptation

Outcome variable	Variable categories	Agroforestry adaptation decision				Total		Statistical value	
		Adaptors		Non-adaptors					
		Freq	%	Freq	%	Freq	%	t-value	p-value
Climate resilience due to agroforestry adaptation	No	64	40.25	212	94.22	276	71.88	14.32	0
	Yes	95	59.75	13	5.78	108	28.13		
	Total	159	41.41	225	58.59	384	100		

The results presented in Table 5 provide a comprehensive overview of the relationship between agroforestry adaptation and climate resilience among farmers in the Kochere, Wonago, and Yirgachefe districts of the Gedeo Zone. The data reveals significant differences between agroforestry adopters and non-adopters, with implications for agricultural practices, policy-making, and community engagement.

3.4 Climate Resilience Outcomes Based on Adaptation Decision

Among agroforestry adopters, 59.75% (95 out of 159) report experiencing climate resilience due to their agroforestry practices. This indicates a strong positive perception of the benefits associated with agroforestry in enhancing their resilience to climate impacts.

In stark contrast, only 5.78% (13 out of 225) of non-adopters report experiencing similar benefits, with the overwhelming majority (94.22%) not perceiving any climate resilience from their agricultural practices.

The *t*-value of 14.32 and a p-value of 0.000 indicate a highly significant difference between the two groups regarding their experiences of climate resilience. This suggests that the adoption of agroforestry is strongly associated with improved climate resilience outcomes for farmers.

The stark contrast in climate resilience perceptions between adopters and non-adopters highlights the critical role that agroforestry can play in enhancing farmers' adaptive capacity to climate change. Agroforestry systems, which integrate trees with crops and/or livestock, provide multiple benefits, including improved soil health, increased biodiversity, and enhanced microclimates all of which contribute to greater resilience against climate variability (Nair, 2011).

3.5 Determinants for household's agroforestry based adaptation decision in response to climate change and variability

Binary logit was employed to identify significant factors determines household's agroforestry based adaptation decision and marginal effect after logit was employed to identify the extent to which the factors determines farmers adaptation in response to climate change and variability.

Table 6. Binary logit output of determinants of households decision to adoption of agroforestry to changing climate

Variables	Coef.	Std. Err	*z*	Effect	p-value
Age	0.772	0.160	4.80	0.181***	0.000
Sex	-0.925	0.521	-1.77	-0.226	0.076
Marital status	-0.178	0.214	-0.83	-0.041	0.405
Family size	0.173	0.216	0.80	0.040	0.423
Educational	0.034	0.304	0.11	0.007	0.911
Farm size	0.899	0.202	4.45	0.211***	0.000
Access to basic service	0.557	0.328	1.70	0.131	0.090
Access to market	0.503	0.445	1.13	0.117	0.259
Agroecology	0.074	0.390	0.19	0.017	0.848
Food security status	0.958	0.531	1.80	0.223	0.071
Income	0.500	0.354	1.41	0.115	0.158
Participation in institutions	1.130	0.451	2.51	0.264**	0.012
Wealth and asset	0.568	0.231	2.45	0.133**	0.014

Note: *** and ** indicates the variables are significant at 1% and 5% respectively

The results from the binary logit model presented in Table 6 provide valuable insights into the factors influencing households' decisions to adopt agroforestry practices in response to climate change in the Kochere, Wonago, and Yirgachefe districts of the Gedeo Zone. The coefficients (Coef.), standard errors (Std.Err), z-values, effect sizes, and p-values are critical for understanding these dynamics.

Age: The positive coefficient (0.772) indicates that as age increases, the likelihood of adopting agroforestry increases significantly (p-value: 0.000). Older farmers may possess more experience and knowledge about the benefits of agroforestry and are more willing to invest in long-term sustainable practices. The effect size (0.181) suggests that a one-unit increase in age is associated with an 18.1% increase in the probability of adoption. Older farmers often have deeper ties to their land and a greater understanding of environmental changes, as well as accumulated resources that facilitate initial investments (Mekonnen *et al*., 2020).

Sex: The negative coefficient (-0.925) suggests that being female is associated with a lower likelihood of adopting agroforestry, though this is marginally significant (p-value: 0.076). The effect size (-0.226) indicates that female-headed households are approximately 22.6% less likely to adopt agroforestry compared to male-headed households. Gender disparities in access to resources, education, and decision-making power can hinder women's adoption of agroforestry practices. Addressing these barriers through targeted interventions could enhance women's participation in sustainable agricultural practices (Agarwal, 2018).

Marital Status: The coefficient for marital status (-0.178) is negative but not statistically significant (p-value: 0.405). This suggests that marital status does not have a substantial impact on the decision to adopt agroforestry. Other factors may overshadow the influence of marital status, indicating that social structures or household dynamics might not play a critical role in agroforestry adoption in this context.

Family Size: The positive coefficient (0.173) indicates a slight increase in adoption likelihood with larger family sizes; however, this is not statistically significant (p-value: 0.423). Larger families may have more labor available for implementing agroforestry practices, but this factor alone does not significantly influence adoption decisions.

Educational Level: The coefficient (0.034) is positive but not significant (p-value: 0.911). This indicates that educational level does not significantly influence the decision to adopt agroforestry. This

finding may reflect a gap between formal education and practical agricultural knowledge, suggesting that hands-on training and local knowledge dissemination are crucial for promoting agroforestry (Zomer *et al*., 2016).

Farm Size: The significant positive coefficient (0.899) indicates that larger farm sizes are strongly associated with higher adoption rates of agroforestry practices (p-value: 0.000). An increase in farm size by one unit increases the probability of adoption by approximately 21.1%. Larger farms provide more opportunities for integrating trees into agricultural systems, allowing for diversified income sources and improved resilience against climate variability (Mastrorillo *et al*., 2016).

Access to Basic Services: The positive coefficient (0.557) suggests a potential link between access to basic services and agroforestry adoption, though it is marginally significant (p-value: 0.090). Access to essential services such as water, healthcare, and infrastructure can facilitate the adoption of agroforestry by improving farmers' overall livelihoods and reducing risks associated with climate change (Kiptot & Franzel, 2015).

Access to Market: The coefficient (0.503) indicates a positive relationship between market access and agroforestry adoption; however, this is not statistically significant (p-value: 0.259). Improved market access can enhance farmers' ability to sell agroforestry products, but additional factors may need to be considered to fully understand its impact (Singh *et al*., 2019).

Agro-ecology: The coefficient (0.074) is positive but not significant (p-value: 0.848), indicating that agro-ecological conditions do not significantly influence the decision to adopt agroforestry. This suggests that agro-ecological factors, while important, may not be the primary drivers of adoption decisions in this context.

Food Security Status: The positive coefficient (0.958) suggests that food security status is positively related to agroforestry adoption, approaching significance (p-value: 0.071). Households experiencing food insecurity may be less likely to invest in long-term practices like agroforestry due to immediate survival concerns (Mekonnen *et al*., 2020).

Income: The positive coefficient (0.500) indicates a potential relationship between income and agroforestry adoption; however, it is not statistically significant (p-value: 0.158). Higher income could provide farmers with the resources needed for investment in agroforestry practices, but other barriers might limit this relationship (Zomer *et al*., 2016).

Participation in Institutions: The significant positive coefficient (1.130) indicates that participation in institutions is strongly associated with higher adoption rates of agroforestry (p-value: 0.012). An increase in institutional participation raises the probability of adoption by approximately 26.4%. Engagement with agricultural institutions can provide farmers with valuable resources, training, and support networks essential for successful agroforestry implementation (Kiptot & Franzel, 2015).

Wealth and Asset Ownership: The positive coefficient (0.568) indicates a significant association between wealth/assets and the likelihood of adopting agroforestry practices (p-value: 0.014). Higher asset ownership increases the probability of adoption by approximately 13.3%. Wealthier households may have greater access to resources necessary for implementing agroforestry systems, thereby enhancing their adaptive capacity to climate change (Mastrorillo *et al*., 2016).

3.6 Impact of participating in agroforestry adaptation on climate resilience

To identify the significant impact of participating in agroforestry adaptation on climate resilience, the researchers employed the propensity score matching model. The output of this model is explained in Table 7.

The results presented in Table 7 illustrate the Average Treatment Effect on the Treated (ATT) for climate resilience due to participation in agroforestry among households in the Kochere, Wonago, and Yirgachefe districts of the Gedeo Zone. The data reveals significant differences in climate resilience between agroforestry adopters and non-adopters.

Table 7. Average Treatment Effect on the Treated (ATT) for Climate Resilience Resulting from Participating in Agroforestry

Outcome variable	Sample	Treated	Control	Difference	T-stat	P-value
Climate resilience	ATT	1.1949	0.1155	-1.079	14.32	0.000

The outcome variable, climate resilience, shows an ATT value of 1.1949 (Treated) versus 0.1155 (Control), with a difference of -1.079. This indicates that agroforestry adopters have a substantially higher level of climate resilience compared to the control group (non-adopters). The T-statistic of 14.32 and a p-value of 0.000 confirm that this difference is statistically significant, providing strong evidence that participation in agroforestry enhances climate resilience.

4 Discussions

The adaptation status of farmers to agroforestry practices in Kochere, Wonago, and Yirgachefe districts of the Gedeo Zone reveals notable variation. In Kochere, 65.67% (88 farmers) did not adopt agroforestry, while 34.33% (46 farmers) did. Similarly in Wonago, 62.16% (69 farmers) reported non-adoption, with 37.84% (42 farmers) adopting agroforestry. In contrast, Yirgachefe recorded higher adoption rate of 51.08% (71 farmers), with 48.92% (68 farmers) not adopting. This relatively higher adoption in Yirgachefe may reflect favorable conditions of community engagement and institutional support. Smallholder farmers in the study area perceive climate change as an immediate threat to agricultural productivity (Zomer *et al*., 2016). They report observable shifts in weather patterns, including altered rainfall distribution, rising temperatures, and unpredictability (Mastrorillo *et al*., 2016). These climatic changes adversely affect crop yields, water availability, and overall agricultural output (Zomer *et al*., 2016). Key informants emphasized the challenges posed by erratic weather, such as frequent droughts and irregular rainfall which contribute to crop failures and food insecurity. Farmers struggle to plan effectively due to weather uncertainty (Mastrorillo *et al*., 2016), and water scarcity and heat stress further affect vulnerable crops like coffee, maize, and beans (Nair, 2011; Zomer *et al*., 2016).

To enhance resilience and reduce dependence on monoculture systems, farmers diversify their crop selection (Mastrorillo *et al*., 2016). Agroforestry practices are widely implemented to improve soil health, enhance biodiversity, and generate supplementary income (Zomer *et al*., 2016). These systems contribute to soil conservation, erosion control, and the maintenance of soil fertility (Nair, 2011). In response to water scarcity, farmers adopt water harvesting techniques as a key adaptation measure (Mastrorillo *et al*., 2016). Participants in local networks and extension services further facilitate the adoption climate smart practices (Nair, 2011; Zomer *et al*., 2016). The multifunctional benefits of improved soil quality, increased biodiversity, and enhanced water retention support climate resilience and buffer households against climate induced shocks.

The study finds that the age of the household head positively influences farmers' decision of adopting agroforestry. Older farmers tend to adopt more readily due accumulated agricultural experience and greater capacity to assess the benefits of new technology (Gebre, 2015; Gbetibouo, 2009; Maddison, 2006; Ndambiri, 2012; Nhemachena, 2007). This trend is consistence with findings from Ethiopia and other regions (World Bank, 2008).

Farm size positively correlates with adaptation options. Large landholdings allow for crop diversification, dry season-production, and integration of livestock with diverse cropping systems (Abrham, 2017; Hassan *et al*., 2020; Megersa; 2022; Misganaw *et al*., 2014). However, some studies suggest that farmers with extensive cultivated land may be more risk-averse and less inclined to adopt new practices (Amare; 2017). Drawing from theories of agricultural intensification and risk aversion, larger farms may offer greater flexibility for agroforestry implementation, though decisions remain influenced by individual perceptions, resource availability, and economic consideration (Hassan *et al*., 2020; Mekonen *et al*., 2022).

Participation in local institutions significantly influences adaptation decisions. Institutions whether governmental or civic, political, or private, play a vital role in promoting adaption strategies and fostering

community level responses to climate change (Adger, 2008; Amare, 2017; Belay, 2017; Bekele, 2020). Environmental factors Soil fertility, topography, and water availability also shape adaptation choices (Fissha *et al*., 2019). Understanding local ecological conditions is essential for designing effective strategies that support soil conservation, biodiversity, and microclimate regulation. Supportive policies, including government subsidies, insurance schemes, and extension services, further influence farmers' adaptation decisions (Obayehu, 2014).

The household's wealth status is another determinant of adaptation. Wealthier households are better positioned to invest in agroforestry due to greater access to finance and resources (Obayehu, 2014). In central Kenya, adopters of climate adaptation strategies report higher incomes than non-adopters (Asayehegn, 2017). Increased farm income resulting from adaptation enhances household well-being, especially in Ethiopian, where crop income constitutes a major a major share of household earnings (Fissha *et al*., 2019). These findings underscore the importance of improving household wealth and asset ownership to strengthen adaptation capacity.

Focus group discussions provided rich qualitative insights into the determinants of agroforestry adoption among smallholder farmers in the Gedeo Zone. Perspectives either farmer groups highlighted the influence of socio-economic dynamics, environmental conditions, resource access, policy framework, market forces, and cultural practices. These discussions revealed the complex interplay of factors shaping adaptation decisions and emphasized the need for context-specific interventions.

5 Conclusion

The study reveals that agroforestry adoption in the Gedeo Zone is shaped by a complex interplay of social, economic, and institutional factors. These dynamics highlight the importance of tailored strategies that address local barriers while leveraging existing strengths. Promoting agroforestry requires more than technical solutions it demands inclusive policies that consider age, gender, education, and access to resources. The demonstrated link between agroforestry and climate resilience reinforces its role as a cornerstone of sustainable rural development. To unlock its potential, coordinated efforts among policymakers, community leader, and development partners are essential. Such efforts can foster equitable participation, strengthen adaptive capacity, and ensure long-term food and livelihood security across the region.

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Competing interest

The authors declare that there are no conflicts of interest related to this manuscript.

Authors contributions

Tigistu Gezahegn contributed to the conceptualization, data collection, formal analysis, investigation, project administration, visualization, and overall original manuscript writing. Mesele Negash played a key role in designing the methodology, supervising, validating, and reviewing the manuscript with constructive comments. Eshetu Yirsaw made significant contributions by reviewing, supervising, validating, and providing comments on the manuscript.

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Epidemiology and Community Knowledge of Bovine Trypanosomiasis in Yirgacheffe District, Southern Ethiopia: A Cross-Sectional Study

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Abstract

A cross-sectional study was conducted from December 2021 to June 2022 in selected kebeles of Yirgacheffe District, Southern Ethiopia, to assess the epidemiology of bovine trypanosomiasis and farmers' knowledge, awareness, and management practices. A total of 384 indigenous cattle were systematically sampled and examined using the buffy coat technique and packed cell volume (PCV) determination. In addition, 200 cattle-owning households were purposively interviewed using semi-structured questionnaires. Data were analyzed using SPSS version 25, employing descriptive statistics, t-tests, chi-square tests, and odds ratios (ORs) with 95% confidence intervals. Trypanosomiasis infection prevalence ranged from 8.6% to 11.9% across origins (OR = 1.30–1.55). Infection was higher in adults (15.48%, OR = 1.56) and in poorly conditioned cattle (6.02–21.1%, OR = 2.16–3.16). Sex showed no significant effect, indicating that age and body condition are the main determinants of trypanosome infection risk. Community findings showed that 67% of farmers recognized bovine trypanosomiasis and 85% were aware of its clinical signs. Most respondents relied on trypanocide drugs and insecticide application, and 77.5% were willing to pay for improved veterinary services. Despite this awareness, ongoing transmission suggests gaps in vector control, diagnostics, and extension services. In conclusion, bovine trypanosomiasis remains an important constraint to cattle productivity in Yirgacheffe District, with anemia as a key pathological indicator. Integrated, area-specific control strategies —including targeted vector management, strengthened veterinary services, routine PCV monitoring, and farmer-focused extension —are essential for sustainable disease control.

Keywords/Phrases: Anemia, Bovine trypanosomiasis, Community knowledge, Epidemiology, Ethiopia

1 Introduction

Livestock production is central to rural livelihoods, food security, and national economies across sub-Saharan Africa, particularly among smallholder farming communities, where it provides income, nutrition, draught power, and improves soil fertility. However, its contribution is severely constrained by tsetse-transmitted African animal trypanosomiasis, one of the most economically devastating livestock diseases on the continent. The disease affects more than 50 million cattle across over 10 million km² of tsetse-infested land, leading to substantial losses in milk and meat production, fertility, draught power, and animal survival. As a result, it undermines agricultural development and perpetuates rural poverty (Leta *et al*., 2016; Shaw *et al*., 2014; Auty *et al*., 2022).

In Ethiopia —where the livestock sector contributes approximately 45% of the agricultural gross domestic product and supports over 80% of the rural population —bovine trypanosomiasis, caused mainly by *Trypanosoma congolense*, *T. vivax*, and *T. brucei* and transmitted predominantly by tsetse flies (*Glossina* spp.), remains a major constraint to livestock productivity and land use (FAO, 2023). Large areas of

fertile land remain underutilized due to persistent tsetse infestation, particularly in southern Ethiopia, where the disease has been endemic for decades despite repeated control efforts. In districts such as Yirgacheffe, earlier studies reported infection rates as high as 25.6% in some localities (Mengistu, 2002). Although vector control and chemotherapy programs have been implemented, recurrent outbreaks continue to compromise livestock productivity and, in some cases, force households to abandon cattle rearing (Alemayehu *et al*., 2021).

Despite the sustained burden of the disease, most previous studies in the area have focused primarily on parasitological prevalence and vector distribution, with limited attention to farmers' knowledge, perceptions, and disease management practices. This gap is important because community awareness and behavior strongly influence treatment-seeking, compliance with control measures, and the long-term sustainability of interventions. Accordingly, this study aimed to assess the epidemiology of bovine trypanosomiasis alongside farmers' knowledge, awareness, and management practices in Yirgacheffe District, Southern Ethiopia, using an integrated cross-sectional approach that combines laboratory-based parasitological analysis with community-level data.

2 Materials and Methods

2.1 Study Area

The study was conducted in Yirgacheffe District, one of six districts in the Gedeo Zone of Southern Ethiopia. The district covers an area of about 266 km^2 and lies between 6°06' – 6°29'N latitude and 38°09' – 38°31'E longitude. It has an estimated human population of 246,573 (87% rural) with a high population density of 933 persons km^2 and an average landholding of 0.65 hectares, which is below the national rural average.

Agro-ecologically, the district is mainly '*Weina Dega*' (93%), with elevations of 1,501–3,000 meters above sea level, annual rainfall of 1,201–1,800 mm, and temperatures ranging from 15.1°C to 20°C. The study focused on four kebeles: Hafurssa Harranji, Hafurssaworabi, Harru, and Chirku-Tutitti (Figure 1), with approximately 3,190 people living in 726 households.

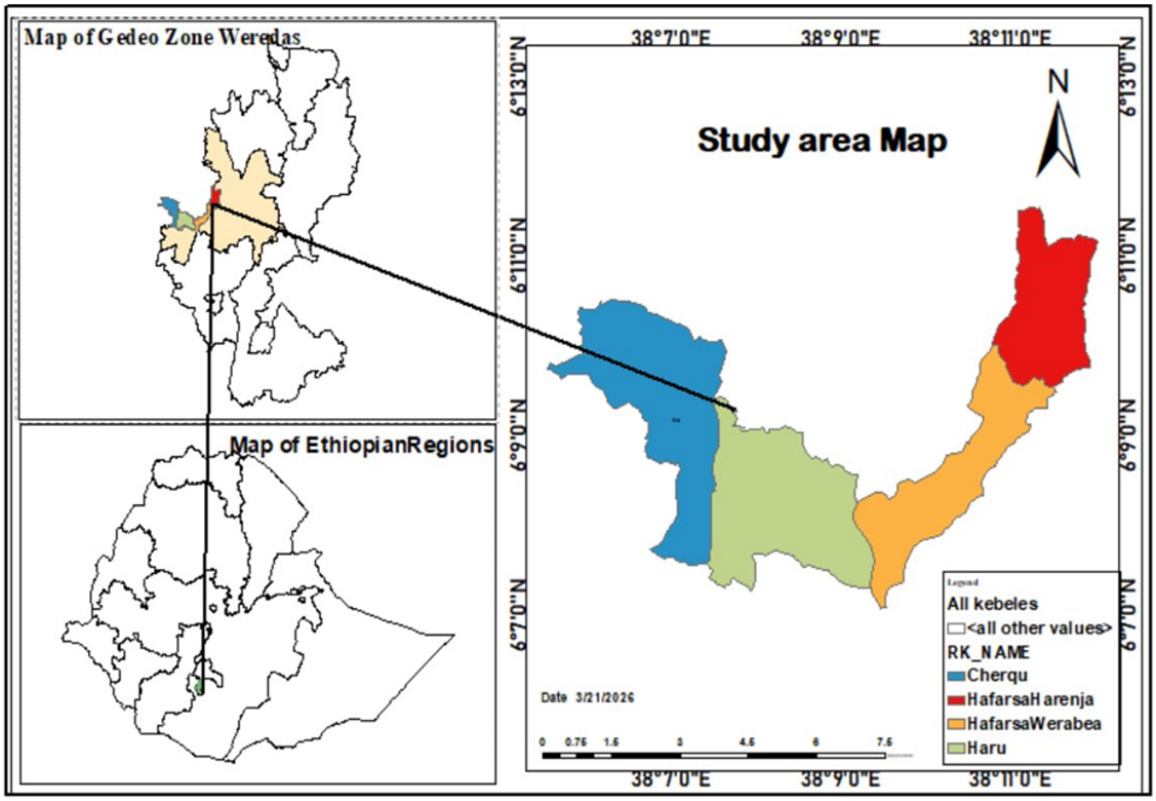


Figure 1. Map of the study area

In the study area, livestock —predominantly indigenous cattle (96%) —are vital for draft power, milk, meat, and manure. Trypanosomiasis is the most significant cattle health challenge (Mebrate *et al*., 2022).

2.2 Study Design

This study employed a cross-sectional design conducted from December 2021 to June 2022 in selected kebeles of Yirgacheffe District, Southern Ethiopia. The cross-sectional design was used to assess the prevalence of bovine trypanosomiasis, associated hematological alterations, and community perceptions during the study period. The methodology integrated parasitological examination of cattle blood with a socioeconomic perception survey of cattle owners, enabling a comprehensive evaluation of the biological, ecological, and socio-economic dimensions of the disease.

2.3 Study Population

The study population comprised indigenous zebu cattle managed under traditional extensive production systems and cattle-owning households residing in the four selected kebeles. In the study area, cattle are the primary source of draft power, milk, meat, and household income. Cattle population estimates for the selected kebeles were obtained from the woreda livestock office and are presented in Table 1 below. In addition, local farmers participated in the perception survey to provide insights into community-level knowledge and management practices.

Table 1. Herd composition by age and sex categories across selected kebelesy

Kebele	Herd composition age in years				
	Oxen ≥ 5	Cows ≥ 5	Heifers < 5	Bulls < 5	Older ≥ 10
Hafurssa Harranji	300	410	215	350	85
Haffursa Worabi	1700	1405	901	98	1451
Haru	445	395	360	132	158
Chirku – Tuttit	700	638	438	366	660
Total	3145	2848	1914	946	2354

2.4 Sample Size Determination

Cattle Sample Size

The sample size for parasitological examination was determined using the standard formula for estimating prevalence in a cross-sectional study (Thrusfield, 2007):

This assumption was made due to the absence of previous prevalence data in the specific study area.

$$n = \frac{1.96^2 \times P_{exp}(1 - P_{exp})}{d^2}$$

Where:

n = required sample size
Pexp = expected prevalence (50%)
d = desired absolute precision (5%)
1.96 = Z-value at 95% confidence level

In the absence of prior prevalence data specific to the study area, 50% expected prevalence was assumed to maximize sample size and statistical precision. Accordingly, 384 cattle were sampled.

For the perception and socioeconomic survey, 200 cattle-owning households were included. This sample size was selected to balance statistical representativeness, logistical feasibility, and time constraints, while ensuring adequate coverage of all four kebeles. The number allowed proportional representation across kebeles and is consistent with similar community-based livestock perception studies conducted in Ethiopia (Gizaw *et al*., 2020). Cattle were selected using a systematic random sampling approach, with sampling intervals determined by herd size to ensure equal selection probability. Livestock owners were selected through purposive sampling based on cattle ownership, farming experience, and willingness to participate. Purposive sampling may introduce selection bias, as surveyed households may not fully represent all cattle owners in the district; this was considered during the interpretation of perception-related findings.

2.5 Data Collection Methods

Parasitological Examination

Blood samples of 10 ml were aseptically collected from the ear vein of each selected animal into heparinized microhematocrit capillary tubes, sealed, and centrifuged at 12,000 rpm for 5 minutes (Murray *et al*., 1977). Packed Cell Volume (PCV) was measured using a microhematocrit reader, and cattle with PCV < 25% were classified as anaemic (Van den Bossche & Rowlands, 2001). Parasite detection was performed using the buffy coat technique: the tube was broken above the buffy coat, the content was placed on a glass slide, covered, and examined under a phase-contrast microscope at 400× magnification (Paris *et al*., 1982). Trypanosome species were identified based on morphology and motility, focusing on *T. congolense* and *T. vivax*, the predominant species in Ethiopia (Radostits *et al*., 2007).

Perception and Socioeconomic Survey

A semi-structured questionnaire was administered to 200 purposively selected cattle-owning households across the four kebeles. It assessed awareness of trypanosomiasis symptoms and transmission, perceived economic impacts (milk yield reduction, mortality, loss of draft power), treatment and coping strategies, and knowledge of previous control programs. The questionnaire was pretested, translated into Gedeo'fa, and conducted via face-to-face interviews by trained enumerators to ensure clarity and cultural relevance.

Ethical Considerations

Ethical approval was obtained from the Dilla University Research Ethics Review Committee. Animal handling and blood sampling followed international welfare guidelines to minimize stress, and informed verbal consent was obtained from all participating farmers, with assurances of confidentiality and voluntary participation.

2.6 Data Analysis

Data from parasitological and socioeconomic surveys were analyzed using SPSS version 25. Trypanosomiasis prevalence was calculated as proportions, and mean PCV values of infected and non-infected cattle were compared using independent t-tests ($p < 0.05$). Associations between infection and categorical variables were evaluated using the Chi-square (χ^2) test, and the strength of associations was estimated using Odds Ratios (OR) with 95% confidence intervals. Qualitative survey responses were thematically categorized, and frequencies were summarized to identify community knowledge gaps and perception trends.

3 Results

3.1 Community Perception and Parasitological Evidence

A total of 200 cattle-owning households from the four study kebeles participated in the perception survey. Overall, respondents demonstrated a good level of awareness of bovine trypanosomiasis: 67% recognized the disease, and 85% identified its main clinical signs. Most respondents obtained information from local sources, and farmers reported using various treatment and control methods. Most were also aware of the disease's adverse effects on livestock health and productivity, highlighting the importance of community knowledge in disease prevention and control (Table 6).

Parasitological examination of 384 cattle identified 39 positive cases, resulting in an overall prevalence of 10.16%. This finding confirms that bovine trypanosomiasis remains a persistent challenge to livestock health and productivity in Yirgacheffe. Taken together, the community perceptions and parasitological findings highlight the value of combining local knowledge with epidemiological evidence to inform effective disease-control strategies.

3.2 Spatial Distribution and Risk Factors

Origin was significantly associated with bovine trypanosomiasis ($p = 0.005$). Cattle from Haru and Chirku–Tuttit had higher odds of infection, with the highest odds observed among cattle from Chirku–Tuttit (Table 2). Although the 95% confidence intervals for the individual site estimates included unity, indicating uncertainty in these estimates, the overall association suggests that infection risk varied by geographical origin, potentially reflecting differences in vector density and transmission pressure. Age was also significantly associated with trypanosomiasis ($p < 0.001$). Adult cattle had

higher odds of infection than young cattle, possibly reflecting greater cumulative exposure over time. Although the confidence intervals crossed unity, the overall pattern suggests that age may be an important population-level risk factor.

Sex was not significantly associated with trypanosomiasis (p = 0.61). Males had slightly higher odds of infection than females, but the wide, overlapping confidence intervals indicate no clear difference in infection risk between the sexes.

Cattle with medium or poor body condition had higher odds of trypanosomiasis than those with good body condition, although the overall association was not statistically significant (p = 0.517). The highest odds were observed among cattle with medium body condition. The wide confidence intervals indicate limited precision; therefore, the observed pattern should be interpreted cautiously and does not establish an association between body condition and infection.

Table 2. Association between selected risk factors and bovine trypanosomiasis

Variable	Category	No. examined	No. positive	Prevalence (%)	OR (95% CI)	P-value
Origin	Hafurssa Harranji	120	13	10.83	1.30 (0.54–3.12)	0.005
	Haffursa Worabi	105	9	8.57	1.21(0.51–2.23)	
	Haru	58	5	8.62	1.45 (0.61–3.45)	
	Chirku–Tuttit	101	12	11.88	1.55 (0.71–3.67)	
Age	Young	120	12	10.00	1.52 (0.61–3.17)	<0001
	Adult	264	27	15.48	1.56 (0.78–3.15)	
Sex	Male	225	24	10.66	1.54 (0.68–3.57)	0.610
	Female	159	15	9.43	1.23 (0.53–2.26)	
Body condition	Good	19	4	21.05	2.16 (1.10–10.20)	0.517
	Medium	216	13	6.02	3.16 (1.20–12.20)	
	Poor	168	26	15.48	2.85 (1.38–5.90)	

3.3 Species Distribution

Three categories of trypanosome infection were identified among cattle across the four kebeles: *T. congolense*, *T. vivax*, and mixed infections (Table 3). Overall, *T. vivax* was the most frequently detected category (51.3%), followed by mixed infections (30.8%) and *T. congolense* (17.94%).

By kebele, the highest overall prevalence was reported in Chirku–Tuttit (45.6%), followed by Hafurssa Harranji (41.6%), Haru (33.1%), and Hafurssa Worabi (32.9%). *T. congolense* infections were most frequent in Hafurssa Harranji (27.7%), while *T. vivax* infections were most frequent in Hafurssa Worabi (58.3%). Mixed infections occurred most frequently in Hafurssa Harranji (36.9%). The distribution of trypanosome infections differed significantly among kebeles (χ^2 = 10.20, p = 0.005).

Table 3. Species Distribution of Trypanosoma parasites in Various Kebeles

Species	Study site in %				Total Prevalence	χ^2	P-value
	Hafurssa Harranji n=120	Haffursa Worabi n=105	Haru n=85	Chirku & Tuttit n=101	% N=384		
T. Congolese	3(27.7)	1(11.7)	1(11.6)	2(16.8)	7(17.94)		
T. Vivax	6(55.3)	5(58.3)	3(34.8)	6(50.5)	20(51.3)		
Mixed	4(36.9)	3(35.0)	1(11.6)	4(33.7)	12(30.8)		
Total	13(41.6)	9(32.9)	5(33.1)	12(45.6)	39(100)	10.20	0.005

3.4 Prevalence of Trypanosomosis and Packed Cell Volume (PCV)

A total of 384 cattle were examined across the four kebeles, and 39 (10.16%) tested positive for trypanosome infection (Table 4). The highest prevalence was recorded in Chirku and Tuttit (11.88%), followed by Hafurssa Harranji (10.83%), Haru (8.62%), and Hafurssa Worabi (8.57%).

Packed cell volume (PCV) assessment showed that 172 cattle (44.79%) were anemic (PCV < 25%), while 212 (55.21%) had normal PCV levels (PCV $\geq$ 25%). Among the kebeles, the proportion of anemic cattle was highest in Haru (56.90%) and lowest in Hafurssa Worabi (38.10%).

Table 4. Packed Cell Volume (PCV) Distribution and Trypanosomiasis Prevalence in Cattle Across Different Study Areas

kebeles	No. of animals examined	No. of animals positive	PCV < 25%	PCV > 25%
Hafurssa Harranji	120	13(10.83)	51(42.50)	69(57.50)
Haffursa Worabi	105	9(8.57)	40(38.10)	65(61.90)
Haru	58	5(8.62)	33(56.90	25(43.10
Chirku and Tuttit	101	12(11.88)	48(47.52)	53(52.48)
Total	384	39(10.16)	172(44.79)	212(55.21)

The mean packed cell volume (PCV) of cattle varied significantly between anemic and non-anemic animals. Anemic cattle (PCV < 25%) had a mean PCV of 17.35% (95% CI: 17.13–20.48) with a standard deviation of 1.56, whereas non-anemic cattle (PCV $\geq$ 25%) had a significantly higher mean PCV of 22.23% (95% CI: 23.43–24.40) with a standard deviation of 2.20. Overall, the mean PCV across all examined cattle was 21.82% (95% CI: 21.34–22.31; SD = 2.57). The difference in PCV between anemic and non-anemic cattle was statistically significant (P < 0.001), confirming that anemia is a prominent hematological feature in the studied population (Table 5).

Table 5. Comparison of mean packed cell volume (PCV) between trypanosome-infected and non-infected cattle

Variables	PCV range	Mean PCV (%)	95% CI	SD	P-value
Anemic	16-21	17.35	17.13-20.48	1.56	
Non-Anemic	19-29	22.23	23.43-24.40	2.20	<0.001
Total	16-29	21.82	21.34-22.31	2.57	

SD = Standard Deviation

3.5 Community Knowledge, Awareness, and Practices

A survey of 200 cattle-owning households revealed variation in awareness, knowledge, and management practices related to bovine trypanosomiasis (Table 6). Overall, 67% of respondents recognized the disease, while 33% did not (χ^2 = 18.3, p = 0.001), indicating moderate but incomplete community awareness. Awareness of clinical signs was higher, with 85% of respondents familiar with the disease's characteristic signs (χ^2 = 11.4, p = 0.002), suggesting that direct exposure to the disease may enhance farmers' knowledge.

Regarding disease management, 60.5% of respondents relied on public or private veterinary services, whereas 39.5% used traditional remedies (χ^2 = 9.1, p = 0.005). This reflects the use of both formal veterinary services and indigenous practices. Regarding the perceived effects of trypanosomiasis on livestock, 69% of farmers identified reduced milk yield as the main impact, followed by fertility problems (14.5%), weight loss (8.5%), and behavioral changes such as restlessness (8%) (χ^2 = 34.6, p = 0.005). These findings indicate that farmers are aware of both the clinical signs of trypanosomiasis and its broader effects on livestock productivity.

Table 6. Farmers' Perception and Awareness of Bovine Trypanosomiasis in Ethiopia

Variable	Category / Response	Frequency (n)	Percent (%)	χ^2	P-value
Farmers' understanding of trypanosomiasis	Recognized	134	67.0	18.3	0.001
	Not recognized	66	33.0		
	Total	200	100		
Awareness of clinical signs	Yes	170	85.0	11.4	0.002
	No	30	15.0		
	Total	200	100		
Treatment/control measures reported	Supported by veterinary clinic	121	60.5	9.1	0.005
	Traditional/home treatment	79	39.5		
	Total	200	100		
Awareness of effects on livestock	Reduced milk yield	138	69.0	34.6	0.005
	Reduced body weight	17	8.5		
	Makes livestock restless	16	8.0		
	Disturbs fertility period	29	14.5		
	Total	200	100		

3.6 Economic Impact and Preventive Practices

The survey results indicated that 77.5% of respondents recognized trypanosomiasis as a disease affecting their livestock, and 85% were aware of its clinical signs (Table 7). More than half of the farmers (51.5%) perceived the disease as causing major economic losses, while 27.5% and 20.0% reported moderate and minor losses, respectively. Only 1.0% perceived no economic impact.

Regarding control efforts, 77.5% of respondents were willing to pay for improved veterinary services to control trypanosomiasis. Most respondents (93.0%) recognized the role of insects in disease transmission: 44.5% reported being regularly aware of insect transmission, and 48.5% reported being occasionally aware of it. The remaining 7.0% were unaware of insect transmission.

Table 7. Economic Impact and Preventive Practices

Response Options	Frequency (n=200)	Percent (%)
Would You Be Willing to Pay for Improved Veterinary Services to Control Trypanosomiasis?		
Yes	155	77.5
No	35	17.5
Not sure	10	5.0
Economic Impact of Trypanosomiasis Perceived by Farmers		
Major economic loss	103	51.5
Moderate economic loss	55	27.5
Minor economic loss	40	20
No impact perceived	2	1.0
Do You Believe Trypanosomiasis is Transmitted by an Insect Vector?		
Yes, regularly	89	44.5
Occasionally	97	48.5
Not aware of it	14	7.0
Which Preventive Measures Do You Use? (for those who answered Yes above)		
Use of insecticide/chemical spray	110	59.1
Grazing management (avoiding tsetse areas)	37	19.9
Using treated nets or traps	23	12.4
Keeping in the house & smoking	30	16.1

The most commonly reported preventive measure was the use of insecticides or chemical sprays (59.1%), followed by grazing management to avoid tsetse-infested areas (19.9%), traditional practices such as housing animals and smoking (16.1%), and the use of treated nets or traps (12.4%). As these percentages total more than 100%, please clarify whether respondents could report more than one preventive measure.

3.7 Discussions

3.8 Prevalence and Risk Factors

The present study confirms that bovine trypanosomiasis remains an important endemic constraint in the study area, with an overall prevalence of 10.3%. This is consistent with national and regional reports of prevalence ranging from 9% to 11%, despite long-standing vector-control and chemotherapeutic interventions (Abebe, 2005; Leta *et al*., 2016). These findings underscore the continued epidemiological importance of tsetse-transmitted trypanosomiasis in southern Ethiopia.

Geographical origin was significantly associated with infection: cattle from Haru and Chirku–Tuttit had higher odds of infection, with the highest odds observed in Chirku–Tuttit. This finding is consistent with previous studies documenting spatial variation in trypanosomiasis prevalence in relation to differences in vegetation, altitude, tsetse density, and the intensity of local control measures (Dagnachew *et al*., 2015; Tasew & Duguma, 2017). Unlike studies that have identified clearly defined hotspots (Feyissa *et al*., 2011), the absence of a single dominant high-risk area in the present study suggests that transmission may be shaped by multiple interacting ecological and environmental factors.

Age was associated with higher odds of infection, with adults showing greater odds than younger cattle. This pattern is consistent with reports from Ethiopia linking infection risk to cumulative exposure, longer grazing periods, and wider movement ranges in older animals (Feyissa *et al*., 2011; Lelisa *et al*., 2014). However, because the confidence limits crossed unity, this association should be interpreted cautiously. The elevated odds may reflect prolonged exposure rather than an inherent difference in susceptibility.

Sex was not significantly associated with infection. Although males had slightly higher odds, the overlapping confidence intervals indicate no clear difference between the sexes. This is consistent with studies reporting similar prevalence in males and females under comparable management and grazing systems (Abebe, 2005; Leta *et al*., 2016). The finding differs from reports of higher prevalence in males, often attributed to exposure associated with draught work (Lelisa *et al*., 2014), suggesting that sex-related differences may depend on local husbandry practices.

Cattle in medium or poor body condition had higher odds of infection than those in good condition, although the association was not statistically significant. This pattern aligns with previous findings that poor body condition can be an indicator of trypanosomiasis, which is associated with anemia, chronic weight loss, and reduced productivity (Abebe, 2005; Leta *et al*., 2016). The elevated odds observed among well-conditioned cattle should be interpreted cautiously given the small sample size and wide confidence intervals, limitations also noted in other localized studies.

3.9 *Trypanosome* Species

Trypanosoma vivax was the predominant species identified, accounting for 51.3% of infections, followed by *T. congolense* (17.94%) and mixed infections (30.8%). This distribution closely resembles findings from the Gambella Region, where *T. vivax* accounted for approximately half of detected infections (Fantahun *et al*., 2019). By contrast, studies from the Assosa and Metekel zones reported *T. congolense* as the dominant species (Ahmed *et al*., 2024), underscoring regional variation in species composition.

These differences may reflect ecological & epidemiological factors, including vector-species composition, vegetation type, and the presence of mechanical vectors. The predominance of *T. vivax* in the present study is epidemiologically important because this species can be transmitted mechanically by biting flies as well as cyclically by tsetse flies. This may allow it to persist even in areas where tsetse density has been reduced (Abebe, 2005). In contrast, *T. congolense* depends primarily on cyclical transmission, making its prevalence more sensitive to vector-control interventions & local tsetse ecology.

The relatively high proportion of mixed infections (30.8%) suggests that cattle may be exposed to overlapping transmission cycles and multiple vector species. Similar proportions of mixed infections have been reported in southwestern Ethiopia and have been associated with more complex disease dynamics and challenges for effective control (Getachew *et al*., 2019; Gebre *et al*., 2022).

Packed Cell Volume

The mean packed cell volume (PCV) was significantly lower in anemic cattle (17.35%) than in non-anemic cattle (22.23%), demonstrating the hematological impact of trypanosomiasis. The overall mean PCV of 21.82% was below the normal reference range for healthy cattle, suggesting a substantial burden of clinical and subclinical anemia in the study population.

Comparable reductions in PCV have been reported in trypanosomiasis-endemic areas of Ethiopia. Tegegn *et al*. (2021), for example, reported a mean PCV of 23.57% in parasitemic cattle in the South Omo Zone, while Muktar *et al*. (2016) reported a mean of 23.22% in infected cattle in Dugda Dawa. Although the absolute values vary, these studies consistently show lower PCV in infected cattle. Similar findings have been reported in the Wolaita Zone and Amhara Region, where parasitemic cattle had markedly lower PCV values than aparasitemic animals (Ashagrie & Zewde, 2021). This consistency across regions supports the use of PCV as an indicator of disease impact.

Anemia associated with trypanosomiasis is multifactorial and may result from hemolysis, immune-mediated erythrocyte destruction, increased erythrophagocytosis, and suppression of erythropoiesis (Abebe, 2005; Getachew *et al*., 2019). The PCV reduction observed in the present study may reflect prolonged or repeated exposure to infection, potentially compounded by nutritional deficiencies and limited access to veterinary services in extensive production systems.

Influence of *Trypanosome* Species on Anemia Severity

The significant reduction in packed cell volume (PCV) observed in the present study is consistent with findings from previous Ethiopian studies of bovine trypanosomiasis, in which anemia is recognized as a key pathological feature, particularly in cattle infected with *Trypanosoma congolense* in tsetse-infested areas (Abebe, 2005; Getachew *et al*., 2019). Although species-specific comparisons are limited, the marked decline in PCV may reflect common pathogenic processes, including erythrocyte destruction, suppression of bone marrow activity, and immune-mediated hemolysis. These effects may be further exacerbated by mixed infections in naturally exposed cattle.

By contrast, Tesfaye *et al*. (2012) reported no significant changes in PCV among cattle in non-tsetse-infested areas. This difference may reflect less frequent exposure, lower infection pressure, earlier diagnosis, or lower parasitemia. Variation in ecological exposure, study populations, and diagnostic methods may also contribute to differences in hematological findings. These observations highlight the influence of endemicity and methodological factors on PCV outcomes and the need for integrated parasitological, hematological, and molecular approaches to better characterize species-specific pathogenicity in Ethiopia's endemic areas.

3.10 Community Perception

The relatively high level of community awareness observed in the present study (67–85%) suggests that livestock farmers generally have a good understanding of bovine trypanosomiasis. This awareness may reflect repeated exposure to the disease and its visible effects on animal health and productivity. Comparable levels of awareness have been reported in other trypanosomiasis-endemic areas of Ethiopia, where farmers often recognize the disease through its clinical signs and production losses rather than through formal training (Fesseha *et al*., 2022).

Despite this general awareness, nearly one-third of respondents in the present study could not recognize the disease, indicating persistent knowledge gaps that may delay early detection and appropriate intervention. Similar findings have been reported by Kizza *et al*. (2021) and Bemba *et al*. (2023): although farmers were generally familiar with trypanosomiasis, disease control relied heavily on chemotherapy, while preventive measures such as vector control and herd-level management were less widely adopted. This pattern is consistent with the

present findings and suggests that awareness alone may not be sufficient to reduce the disease burden without practical knowledge and effective control strategies.

3.11 Willingness to Pay for Veterinary Services

The high proportion of respondents willing to pay for veterinary services (77.5%) suggests strong awareness of the economic impact of trypanosomiasis. Similar findings were reported by Fesseha *et al*. (2022), who found that farmers in southern Ethiopia were motivated to seek treatment because the disease directly affects milk production, draught power, and household income. This contrasts with findings from some resource-limited or non-endemic areas, where cost remains a major barrier to accessing veterinary care.

However, the continued presence of trypanosomiasis in the study area, despite farmers' expressed willingness to pay, indicates that economic motivation alone may not be sufficient to ensure effective disease control. Structural constraints—including limited diagnostic services, inadequate vector-control infrastructure, irregular veterinary outreach, and a shortage of trained personnel—may prevent farmers from translating this willingness into consistent preventive action. Similarly, Feyera *et al*. (2023) emphasize that successful disease control depends not only on farmers' awareness and willingness but also on the availability, affordability, and quality of veterinary services.

3.12 Economic Impact and Preventive Practices

The present study confirms that livestock farmers perceive bovine trypanosomiasis as a major cause of economic loss, highlighting its continued impact on livestock productivity in the study area. More than half of the respondents reported that the disease causes substantial economic damage, whereas only a small minority considered it to have no economic impact. These findings suggest that farmers have a strong practical understanding of the disease's effects.

This perception is consistent with findings from southwestern Ethiopia, where trypanosomiasis was identified as a major constraint on livestock production because of reduced milk yield, poor body condition, and diminished draught power (Seyoum *et al*., 2016). The high levels of awareness of clinical signs and transmission reported in the present study also align with the findings of Feyisa *et al*. (2020). However, they contrast with reports from low-prevalence and non-endemic areas, where limited awareness among livestock keepers has been identified as a barrier to early detection and control.

Whereas some studies have reported that control efforts rely mainly on chemotherapy, with limited emphasis on prevention (Bemba *et al*., 2023), the comparatively greater adoption of preventive measures observed in the present study may indicate a more proactive approach among local livestock keepers. This difference could reflect variation in access to extension services, exposure to vectors, or farmers' accumulated experience in managing the disease.

4 Conclusion and Recommendations

4.1 Conclusion

Bovine trypanosomiasis remains a significant constraint on cattle production in Yirgacheffe, with an overall prevalence of 10.16% and marked spatial variation. Prevalence was particularly high in Chirku–Tuttit, where local ecological conditions may favor transmission. Adult cattle were more frequently affected, and *Trypanosoma vivax* was the predominant species. The significantly lower packed cell volume (PCV) values in infected animals confirm anemia as an important pathological outcome and support the use of PCV as a practical indicator of disease impact. Despite relatively high levels of farmer awareness and willingness to invest in veterinary services, continued transmission points to gaps in diagnostic capacity, service delivery, and the implementation of effective control measures.

4.2 Recommendations

- Strengthen veterinary and diagnostic services at the community level to improve access, early detection, and timely treatment of infected animals.
- Implement targeted vector control strategies in high-risk areas, integrating insecticide application, tsetse trapping, and habitat management.

- Promote routine PCV-based monitoring of cattle to identify infection early and assess herd health status.
- Ensure rational use of trypanocide drugs to prevent resistance development and enhance treatment efficacy.
- Enhance extension and awareness programs to empower farmers with knowledge of prevention, early detection, and proper animal management practices.
- Integrate trypanosomiasis control into livestock development policies and food security programs to ensure sustainability and coordinated action across sectors.

Limitation of the Study

The study relied on the buffy coat technique for parasite detection. Because this method is less sensitive than advanced diagnostic approaches, it may have underestimated the true prevalence. The absence of molecular diagnostics also limited precise species confirmation and the detection of low-level infections. In addition, data were collected during a single season and may not capture seasonal variations in disease occurrence or entomological factors. These limitations should be considered when interpreting and extrapolating the findings. Future studies should use more sensitive diagnostic methods and collect data across multiple seasons.

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Conflicts of interest

The authors declare that there are no conflicts of interest related to this manuscript.

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