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The effect of renewable energy on Green Economy Development: evidence from the Ethiopian economy running from the year 1990 to 2022

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Abstract

Ethiopia is currently seeing a sharp rise in interest in modern clean energy generation as a means of achieving environmental and economic sustainability. However, there is still a lack of empirical study examining how investments in contemporary clean energy impact Ethiopia's progress toward a green economy. The impact of renewable energy on Ethiopia's green economy development was examined in this study, with a focus on the relationship between modern clean energy consumption, economic growth, and environmental quality between 1990 and 2022. The study used yearly time series data from the International Energy Agency (IEA), the Global Carbon Atlas (GCA), and the World Development Indicators (WDI). The auto regressive distributed lags (ARDL) econometric estimation method was applied to analyze the data. The results indicated that the utilization of non-renewable energy, biomass, and modern clean energy were significant contributors to the variations in carbon dioxide emissions in Ethiopia. However, only contemporary clean energy exhibited statistical significance in relation to long-term economic growth. The findings imply that the adoption of green energy sources, such as hydro, wind, and solar energy, has the potential to reduce carbon emissions while enhancing output. It is advised that Ethiopian authorities prioritize the advancement of renewable energy sources to avert the economy from becoming increasingly carbon-intensive in the future. This necessitates robust collaboration among policymakers, the government, and international cooperation organizations to enhance investment in modern clean energy and ensure sustainable development both environmentally and economically.

Keywords/Phrases: Economic growth, Environmental quality, Green development, Modern clean energy

1 Introduction

Ethiopia, recognized as one of the least developed countries globally, has recently witnessed a notable surge in its economic output, positioning itself among the fastest-growing economies worldwide. According to the data available, Ethiopia demonstrated an impressive growth trajectory, achieving an average annual growth rate of 9.3% from 2013 to 2018 (NBE, 2020). This growth was primarily propelled by increased industrialization and urbanization, which were significantly supported by a rise in energy consumption (Teka *et al*, 2020).

Ethiopia aspires to attain middle-income status by the year 2025, leveraging its recent achievements in robust economic growth. The realization of this objective will largely hinge on enhancing productivity within the agricultural sector, broadening the industrial base, and fostering growth in international trade, as delineated in the Growth and Transformation Plan (GTP) (FDRE, 2011). In essence, the ambition for industrialization, particularly heavy industrialization, leads to more energy-intensive economic activities as the nation strives to achieve middle-income status.

It is widely acknowledged that energy infrastructure serves as a vital element affecting a nation's economic growth and development, often described as the lifeblood of the contemporary economy (Kulionis, 2013). Because it increases the productivity of other resources and raises living standards, energy is a crucial input in production and is necessary for a nation's economic and social advancement.

Nevertheless, as noted by Kulionis (2013), the increasing demand for energy to support economic activities also exacerbates environmental issues. The excessive consumption of energy results in the release of significant quantities of carbon dioxide, which has been recognized as the leading cause of global warming and climate change.

Recently, the demand for energy in Ethiopia has surged in response to the nation's accelerating industrialization and rapid population growth. In other words, the economic and demographic expansion of the country has led to a notable increase in energy consumption.

According to the International Energy Agency's report (2020), statistics indicate that Ethiopia's total final energy consumption increased from 16,771 KTOE in 1990 to 40,717 KTOE in 2018, representing a rise of 142.78%. This trend suggests that the demand for energy in Ethiopia has been growing in close alignment with the country's economic and population expansion.

Despite the increasing energy requirements, the structure of Ethiopia's energy consumption remains inefficient, environmentally harmful, and primarily reliant on biomass energy sources, which constitute approximately 88% of total consumption (MoWE, 2012). Given this consumption pattern, the anticipated rise in energy demand is expected to worsen the country's environmental degradation.

In light of these challenges, and in response to recommendations from environmentalists and economists to redirect growth objectives from traditional economic development to more environmentally sustainable practices, as noted by Alam *et al.* (2016), Ethiopia has adopted the "Climate Resilient Green Economy (CRGE)" strategy. As the country moves toward a green economy, this project seeks to protect it from the negative effects of global warming. Through this strategy, Ethiopia expresses its goal to attain middle-income status by 2025 while concurrently safeguarding environmental quality (FDRE, 2011). This demonstrates the country's dedication to pursuing economic progress in a more sustainable fashion.

Ethiopia's government plans to develop clean energy, particularly hydropower, wind, geothermal, and solar power, as well as non-renewable and combustible renewables and waste, because of the country's tropical location and the abundance of opportunities for contemporary environmentally friendly energy sources. The objective is to fulfill Ethiopia's desire to create an ecologically sensitive economy.

According to available data, Ethiopia's performance in modern clean energy development has been outstanding. From 1980 to 2018, the country's hydroelectricity net generation climbed from 5,184.04 Terajoules to 123,790.46 Terajoules, demonstrating an exceptionally high average growth rate of 58.66%.

Wind energy investment in Ethiopia has also increased significantly. Wind electricity net generation has grown from 307.53 Terajoules in 2011 to 5,119.59 Terajoules in 2019, reflecting a 173.86% average growth rate during this period. Solar energy generation has also increased from 1.04 Terajoules in 2008 to 192.1 Terajoules in 2019 (IEA, 2020).

The key concern here is: to what extent can renewable energy developments, particularly modern clean energy, contribute to the development of Ethiopia's green economy? Since the goal of green economic growth is to achieve middle-income status by increasing output while maintaining environmental quality, it is important to analyze the impact of current clean energy initiatives from both an economic and environmental perspective.

A deeper comprehension of the causal links between renewable energy, economic growth, and environmental conditions is required in order to create effective policies. This will help determine how renewable energy developments can best support Ethiopia's ambition of transitioning to a green economy and achieving its middle-income target by 2025 while safeguarding environmental quality.

The connection between environmental conditions and some of their underlying causes in both prosperous and poor countries has been the subject of various economic research studies for a long time. Numerous studies have examined the relationship between environmental deterioration and economic activity since the groundbreaking work of Grossman and Krueger (1991), including Wolde (2015) and Hamilton & Turton (2002).

Furthermore, a number of research have examined the relationship between economic activity, environmental quality, and total energy consumption (Zakarya *et al.*, 2015; Wolde *et al.*, 2016; Kebede, 2017). The impact of traditional and modern energy use on environmental quality as determined by carbon dioxide emissions has also been the subject of some recent empirical studies (e.g., Jebli and Youssef, 2015).

To the best of the researchers' knowledge, however, no study has explicitly looked at how renewable energy—especially contemporary clean energy—affects the growth of green economies. This investigation aims to contribute to the existing body of knowledge and the ongoing debate on environmental issues by employing the Autoregressive Distributed Lag (ARDL) model, a recently developed co-integration method, to analyze this relationship.

2 Research question

The following research question guides this study:

- Does moving the country's energy consumption structure toward modern clean energy actually help the country accomplish the goal of the Climate Resilient Green Economy (CRGE) plan by preserving environmental quality?

- Does shifting the nation's energy consumption structure to modern clean energy genuinely help it achieve the Climate Resilient Green Economy (CRGE) strategy's objective of increasing output?

- Which source of energy has the most effect on Ethiopia's environmental quality and economic growth?

3 The study Approach

3.1 Data sources and types

The study used annual time series data covering 32 years, from 1990 to 2022, to examine the impact of renewable energy, especially contemporary clean energy consumption, on Ethiopia's green economic development. This period of time was chosen to guarantee the availability of pertinent data for the study.

The Environmental, Forest, and Climate Change Commission of Ethiopia (EFCCC), World Development Indicators (World Bank), Global Carbon Atlas (GCA), and the International Energy Agency (IEA) were the sources of the data.

3.2 Model specification

Model One: In their empirical analyses, some empirical studies in economic literature often used carbon dioxide emission as a primary indicator of environmental quality (Kebede, 2017; Oh and Bhuyan, 2018). They utilized it as an essential environmental quality indicator based on the three criteria listed below. To begin with, it is the primary type of gas that results from activities associated with energy. Second, it is a predominant greenhouse gas found throughout the planet's atmosphere and is responsible for approximately 75 percent of worldwide pollution. Third, it is being minimized in order to benefit the environment. Following the preceding studies and taking into account the conditions described above, the current study additionally proxies environmental quality by carbon dioxide emission.

Several previous studies, such as Kebede (2017), Poku (2016), Wolde *et al.* (2016), Halicioglu (2009), and Oh and Bhuyan (2018), have included economic growth and energy use indicators in their modeling approaches to investigate the implications of these factors on carbon dioxide emissions. These factors were found to be relevant and to affect carbon dioxide emissions in a statistically significant way.

Following the precedent set by prior research, the current study employs an environmental quality model proxied by carbon dioxide emissions, with energy consumption considered as a determining factor, in order to assess the environmental impact of modern clean energy use.

Given this, the study's model, which takes the following form, seems to be in line with the larger body of research on the factors influencing carbon dioxide emissions:

$$CO_2 = f(EC_t) \tag{1}$$

Where CO_2 = carbon dioxide emission at year t and is a proxy for environmental quality, EC_t = total energy consumption at a year t.

Nevertheless, the current study's objective is not entirely in line with this generic model. The energy consumption variable in the aforementioned model needs to be further broken down because the goal of this study is to investigate how the current use of clean energy affects environmental quality as assessed by carbon dioxide emissions.

Specifically, the energy use variable (ECt) in Equation (1) should be subdivided into three components: modern clean energy use (MCEt), non-renewable energy use (NREt), and biomass energy use (BEt). This disaggregation will provide a clearer policy context and better align with the study's goal.

Additionally, other relevant factors, such as economic and demographic variables (e.g., population growth, urbanization, economic growth), can be included to more comprehensively describe the environmental quality model in the context of Ethiopia.

Therefore, the following reduced-form model is suggested to evaluate the variables of interest's possible environmental impact:

$$CO_2 = f(MCE_t, NRE_t, BE_t, GDPP_t, POP_t, UPG_t) \tag{2}$$

Where MCE_t stands for modern clean energy consumption at period t, NRE_t stands for non-renewable energy consumption at period t, BE_t stands for biomass energy consumption at period t, $GDPP_t$ stands for output per capita at period t, POP_t stands population at period t, and UPG_t stands for urbanization at period t.

Equation (2) indicates that Ethiopia's real GDP per capita, population, urbanization, use of contemporary clean energy, non-renewable energy, and biomass energy can all be environmental drivers.

Model Two: The current investigation utilized the augmented Solow model and the endogenous growth framework to assess the growth implications of renewable energy, particularly modern clean energy. The GDP growth equation was specified based on the theoretical underpinnings of the Solow (1956) and endogenous growth models, which can be summarized as follows:

$$Y = f(K, HK, LF, A) \tag{3}$$

Where Y stands for economic growth, K stands for Capital stock, HK stands for human capital, LF stands for labor force, and A stands for technology.

To determine whether the shift in the energy consumption structure toward modern clean renewable energy contributes to the country's economic growth, the current study employed an augmented Solow model and an endogenous growth model. In these models, modern clean energy consumption (MCE) is included as an input alongside capital stock (K) and human capital (HK). Other energy variables, such as non-renewable energy use (NRE) and biomass energy consumption (BE), are also taken into account.

In order to reduce the possibility of omitted variable bias and examine their relative effects on the nation's economic growth, these extra energy variables were included. Consequently, the following is the final growth model specification:

$$GDPPC_t = f(K_t, HK_t, MCE_t, NRE_t, BE_t) \tag{4}$$

Where K_t stands for capital formation at period t, HK_t stands for human capita at period t and all the remaining variables in the models are as defined above.

Lastly, all of the variables in the equations were converted into their logarithmic representations for estimation purposes. There are various advantages to this change. First, it lessens the influence of possible outliers and big coefficients, as well as the volatility in the data series. Secondly, it makes it possible to determine approximate growth rates or to capture growth effects. Elasticities are then deduced from the coefficients.

Elasticity's are particularly informative, as they represent the responsiveness of the dependent variable to changes in the independent variables. Therefore, the empirical models of economic growth and the associated carbon dioxide emissions (in Equations (2) and (4)) can be clearly represented as follows:

$$lnCO_{2t} = \theta_0 + \theta_1 lnMCE_t + \theta_2 lnNRE_t + \theta_3 lnBE_t + \theta_4 lnGDPPC_t + \theta_5 lnPOP_t + \theta_6 lnUPG_t + e_t \quad (5)$$

$$lnGDPPC_t = \alpha_0 + \alpha_1 lnK_t + \alpha_2 lnHK_t + \alpha_3 lnMCE_t + \alpha_4 lnNRE_t + \alpha_5 lnBE_t + e_t \quad (6)$$

Where *ln*= is natural logarithm, e_t = is disturbance term, θ_s and α_s in equation (5) and (6), respectively are elasticities. All variables in the models are as defined above.

3.3 Method of Estimation

As carried out earlier by Kamran *et al.* (2020) and Jebli and Youssef (2015b), the current study relied on the bound testing procedure recommended by Pesaran *et al.* (2001) to assess both the short-term and long-term implications of each of the independent variables on both environmental quality and economic growth. Compared to other common time series data models, the ARDL model, which is based on the bound co-integration technique, is preferred as it can be applied regardless of whether the regressors are I(1) or I(0). The following equations describe the ARDL Bound testing approach:

$$\Delta lnCO_{2t} = \theta_0 + \theta_1 lnMCE_{t-1} + \theta_2 lnNRE_{t-1} + \theta_3 lnBE_{t-1} + \theta_4 lnGDPPC_{t-1} + \theta_5 lnPOP_{t-1} + \theta_6 lnUPG_{t-1} + \sum_{j=1}^{n} \beta_{1j} \Delta lnCO_{t-j} + \sum_{j=1}^{n} \beta_{2j} \Delta lnMCE_{t-j} + \sum_{j=1}^{n} \beta_{3j} \Delta lnNRE_{t-j} + \sum_{j=1}^{n} \beta_{4j} \Delta lnBE_{t-j} + \sum_{j=1}^{n} \beta_{5j} \Delta lnGDPPC_{t-j} + \sum_{j=1}^{n} \beta_{6j} \Delta lnPOP_{t-j} + \sum_{j=1}^{n} \beta_{7j} \Delta lnUPG_{t-j} + U_t \quad (7)$$

$$\Delta lnGDPPC_t = \alpha_0 + \alpha_1 lnK_{t-1} + \alpha_2 lnHK_{t-1} + \alpha_3 lnMCE_{t-1} + \alpha_4 lnNRE_{t-1} + \alpha_5 lnBE_{t-1} + \sum_{j=1}^{n} \beta_{1j} \Delta lnGDP_{t-j} + \sum_{j=1}^{n} \beta_{2j} \Delta lnK_{t-j} + \sum_{j=1}^{n} \beta_{2j} \Delta lnMCE_{t-j} + \sum_{j=1}^{n} \beta_{3j} \Delta lnHK_{t-j} + \sum_{j=1}^{n} \beta_{4j} \Delta lnNRE_{t-j} + \sum_{j=1}^{n} \beta_{5j} \Delta lnBE_{t-j} + U_t \quad (8)$$

β_s captures the short-term elasticities of growth and environmental quality with respect to their respective determinant variables. The ongoing link between the model variables is represented by the coefficients θ_s and α_s in equations (7) and (8), respectively. n is the length of the model variables' lag, and Δ implies the difference operation.

3.4 Estimation procedure

Finding out whether the variables under investigation have a long-term relationship is the main objective of this analysis. In order to do this, the researchers have assessed the order of integration of each variable using unit root tests, such as the Phillips-Perron and Augmented Dickey-Fuller tests. This enables them to calculate the number of times a variable must be differentiated in order to reach stationarity. The researchers can proceed with regression analysis to provide accurate forecasts and conduct policy research after the variables have been confirmed to be stationary.

Following the completion of the stationarity tests, the Bound test was utilized to determine if the variables exhibit a long-term co-integrating relationship. Furthermore, the researchers conducted several model diagnostic tests to verify the precision and stability of the final model. These tests encompass the functional form test, normality test, serial correlation test, and heteroscedasticity test. Additionally, the CUSUM and CUSUMSQ tests were employed to evaluate the model's robustness and stability over time.

4 Results and Discussions

4.1 Environmental Quality Equation of Ethiopia

To tackle the problem of spurious regression in the assessment of co-integration within time-series data, it is essential to accurately assess the stationarity of the foundational data series. The application of least squares regression to non-stationary, independent datasets often lead to spurious regression. In these instances, despite the lack of a true relationship between the series, a misleadingly significant statistical connection may be incorrectly identified. This can lead to conclusions about the behavior of the indicators at a specific point in time, without accurately capturing the trends over the years under consideration.

Evaluating the stationarity of the variables is a fundamental task in time series analysis. It is recommended to thoroughly investigate whether the data are stationary or non-stationary. Pre-estimation tests, such as unit root and co-integration tests, should be performed and discussed before estimating and interpreting the study's specified environmental quality equation. Both post-estimation tests and the corresponding findings should then be presented.

4.1.1 Unit root test

Regardless of whether the variables are I (0) or I (1) integrated, the ARDL (Autoregressive Distributed Lag) specification can be formed after it is determined that the model variables are integrated of order less than two. However, it would not be suitable to use the ARDL specification when there are I (2) or higher integrated variables.

In order to ascertain the indicators' integration order, this study employed the conventional Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. The Schwarz Bayesian Information Criterion (SBIC) was used to automatically determine the ideal lag times for the experiments. The comparison of the test statistics to the critical values and the corresponding p-values determined whether the null hypothesis of the unit root tests, which suggests the non-stationarity of the series, was accepted or rejected.

Table 1. Unit Root Tests of the Environmental Quality Equation Variables

Variables	Augmented Dickey-Fuller (ADF) and Phillps Perron (PP) Test		
	ADF T-statistics	PP T-statistics	Decision
lnCO_2	0.4329	1.2184	I(1)
D(lnCO_2)	-5.7547***	-6.3754***	
lnCME	1.4644	1.5766	I(1)
D(lnCME)	-3.6920***	-3.8130***	
lnBE	-4.1908***	-8.3005***	I(0)
lnNRE	0.7038	0.8192	I(1)
D(lnNRE)	-4.7582***	-4.7582***	
lnGDPPC	2.009	1.7511	I(1)
D(lnGDPPC)	-4.1557***	-4.2076***	
lnPOP	-5.1324***	-4.3126***	I(0)
UPG	-1.5339	-1.7098	I(1)
D(UPG)	-3.9769***	-3.9698***	

Note: triple stars in the table indicates significance of the test statistics, indicating rejection of the null hypothesis at a 1% level of significance. (Source: own computation using EViews 9.0)

The environmental quality model includes indicators with an integration order of fewer than two, according to the unit root test findings. This meets the prerequisite for applying Pesaran, Shin, and Smith's (2001) bounds testing technique to cointegration. As a result, the ARDL (Autoregressive Distributed Lag) model can be used to evaluate the long-term relationships between the variables in question.

4.1.2 Bound Co-integration Testing of Environmental Quality Equation

The establishment of the integration order is the foundation for assessing the long-run associations between the model indicators. The unit root tests reveal that the series under investigation in the environmental model are a mix of I(0) and I(1) integrated variables.

Given the mixed integration order of the variables, the long-run association between the model indicators has been examined using the bounds testing approach to co-integration.

Table 2 presents the results of the bounds testing procedure conducted on the environmental model. The F-statistic obtained from the test is highly significant, with a value of 9.518193. This F-statistic exceeds the upper bound or I (1) critical values at the 5% level of significance, suggesting the rejection of the null hypothesis of no long-run association among the model indicators, such as carbon dioxide emissions, modern clean energy, biomass energy, non-renewable energy, real GDP per capita, population, and urbanization. This indicates that changes in one variable will have a lasting impact on the others, and vice versa.

Table 2. Bounds Testing for the Environmental Quality Equation

ARDL bounds testing result		
Null-hypothesis: No long-run association among the model variables		
Test-statistics	Value	K
F-statistics	9.518193	6
Critical value bounds		
Significance	I0 Bound	I1 Bound
1 percent	3.15	4.43
2.5 percent	2.75	3.99
5 percent	2.45	3.61
10 percent	2.12	3.23

(Source: own computation using EViews 9.0)

4.1.3 Bound Co-integration Testing of Environmental Quality Equation

Before interpreting the long and short-run elasticities of the environmental quality model, model diagnostic tests like the Breusch Godfrey LM test for serial correlation, the Breusch-Pagan-Godfrey test for heteroscedasticity, the Ramsey Reset test for functional misspecification in the model, and the Jarque-Bera test for normality of the error term were used to ensure the validity and reliability of the estimation. The tests' null hypothesis suggests that the estimations are accurate and legitimate.

Table 3. Model Diagnostics Testing for Environmental Quality Equation

Tests	Method	√F-statistics √Jarque-Bera for normality	P-value
Seral correlation	Breusch Godfrey LM	0.9388	0.4144
Heteroscedasticity	Breusch-Pagan Godfrey	0.8621	0.5897
Functional form	Ramsey Reset	1.0858	0.3139
Normality	Jarque-Bera	3.3839	0.1841

(Sources: own computation using EViews 9.0)

The model diagnostic assessments are provided in Table 3 below. Since the probability values of the tests all exceed the 5% significance level, the null hypotheses of the diagnostic tests cannot be rejected. This indicates that the model is trustworthy for generating predictions and drawing inferences, and there are no econometric issues with the established coefficients.

4.1.4 Model Stability Testing of Environmental Quality Equation

The stability of the long-run coefficients in the environmental quality model has been assessed by employing the CUSUM (Cumulative Sum) and CUSUMSQ (Cumulative Sum of Squares) tests.

Plots of the test statistics at the 5% level of significance can be compared to the critical boundaries to make the assessment. The null hypothesis of coefficient stability may be accepted if the graphs stay inside the crucial boundaries.

The plots of the CUSUM and CUSUMSQ statistics were inside the critical boundaries at the 5% significance level during the time under review, as Appendix A demonstrates. This demonstrates that the calculated coefficients in the environmental quality model are stable.

4.1.5 Long-run and Short-run Estimates of Environmental Quality Equation

Next to the assessment of the integration order of the series, long-run association, model diagnostics, and model stability, the dynamic long-run and short-run coefficients of the ARDL (1, 0, 0, 0, 2, 2, 0) model were evaluated and interpreted.

The estimated coefficients, standard errors, t-values, and probability values from the environmental quality model estimation are shown in Table 4.

Table 4. Long-run and Short-run Estimates of the Environmental Quality Equation

Method: ARDL **Model selected: ARDL (1, 0, 0, 0, 2, 2, 0)**				
Long-run coefficients				
Variables	Coefficients	Standard error	t-statistics	P-values
lnMCE	-0.234596	0.114716	-2.045020	0.0577*
lnBE	4.395273	1.508174	2.914300	0.0101**
lnNRE	0.185574	0.081717	2.270945	0.0373**
lnGDPPC	0.346595	0.227844	1.521196	0.1477
lnPOP	-1.709507	1.287249	-1.328031	0.2028
UPG	-0.018869	0.025934	-0.727606	0.4774
C	-53.570706	14.338129	-3.736241	0.0018***
Short-run coefficients				
D(lnMCE)	-0.295155	0.141650	-2.083690	0.0536*
D(lnBE)	5.529874	1.696130	3.260289	0.0049***
D(lnNRE)	0.233478	0.109226	2.137567	0.0483**
D(lnGDPPC)	0.253128	0.357718	0.707619	0.4894
D(lnGDPPC(-1))	0.546840	0.210915	2.592700	0.0196**
D(lnPOP)	4.116509	1.875618	2.194748	0.0433**
D(lnPOP(-1))	7.470220	2.132907	3.502365	0.0029***
D(UPG)	-0.023740	0.033058	-0.718146	0.4830
ECM-1	-1.258141	0.135778	-9.266194	0.0000***

Note: ***, **, and * indicate statistical significance of the coefficients at 1%, 5,%, and 10% levels of significance, respectively. (Sources: own estimation using Eviews 9.0)

The environmental quality model's results indicate that the long-term elasticity of carbon dioxide emissions in relation to contemporary renewable energy is -0.234596. This shows that a 1% increase in the use of contemporary clean energy will result in a 0.234596% reduction in carbon dioxide emissions in the nation under investigation, assuming all other factors stay the same. This inverse relationship between the two variables is important for policymakers and researchers to understand, as it can inform decisions about energy and environmental policies. The result is in line with previous empirical research. For instance, Adinew M. (2020) supported the findings of the environmental quality model by discovering a statistically significant negative correlation between the use of renewable energy and anthropogenic carbon dioxide emissions in Ethiopia.

Additionally, the finding aligns with other previously conducted empirical works, such as Asongu *et al.* (2019) for 40 African countries, Heryadi and Hartono (2017) for a panel of G-20 countries, Zandi and Haseeb (2019) for Sub-Saharan African countries, and Shafiei (2013) and Khan *et al.* (2021) for developing countries. Additionally, Uğurlu (2022) discovered that the Visegrad Group countries—Poland, the Czech Republic, Hungary, and Slovakia—saw a declining impact of renewable energy use on CO2 emissions.

These empirical studies provide good evidence that investing in modern clean energy can have a significant positive contribution to the environment by limiting the concentration of carbon dioxide emissions.

Given the inverse relationship between modern renewable energy usage and carbon dioxide emissions, expanding the output of modern clean energy can have a positive impact on Ethiopia's environmental quality by limiting the concentration of carbon dioxide in the atmosphere. However, this expansion requires significant investment, which may be challenging for the country.

Nonetheless, the potential advantages of curtailing carbon dioxide emissions and enhancing environmental quality render this investment valuable. Consequently, it is essential for policymakers and stakeholders to collaborate in identifying strategies that promote the adoption of modern clean energy while decreasing dependence on fossil fuels. This may entail the implementation of policies and incentives aimed at fostering investment in contemporary clean energy, in addition to raising public awareness regarding the benefits of minimizing carbon dioxide emissions.

The long-term findings also imply that using more biomass and non-renewable energy sources will increase greenhouse gas emissions and raise carbon dioxide levels. It is determined that the long-run elasticity of carbon dioxide emissions is 0.185574 for non-renewable energy and 4.395273 for biomass energy. This means that a 1% change in these energy sources' consumption will result in variations in carbon dioxide emissions of 4.395273% and 0.185574%, respectively.

Given that biomass energy makes up almost 90% of Ethiopia's total energy composition, the significant impact of biomass energy use on human-induced carbon dioxide emissions is astounding (UNECA, 2014). One of the main causes of the nation's rising carbon dioxide emissions is its significant reliance on wood, wood-derived fuels, and biomass waste consumption—all of which are categorized as primary and environmentally harmful energy sources.

The findings corroborate the results of a study carried out by Brini (2021) for a panel of African nations, which observed a positive and statistically significant relationship between non-renewable energy use and carbon dioxide emissions. This suggests that non-renewable energy use is a significant contributing factor to the increased anthropogenic carbon dioxide emissions in the country under study.

According to the environmental quality model, over the long term, the concentration of anthropogenic emissions in a country is found to be independent of both demographic factors like population and urbanization, as well as macroeconomic factors like real gross domestic product per capita.

Referring back to the defined ARDL (1, 0, 0, 0, 2, 2, 0) model's short-run outcomes, the coefficients of present clean energy, biomass energy, and non-renewable energy use support the long-run case. But when it comes to the use of contemporary renewable energy, the short-term flexibility of carbon dioxide emissions is greater than the long-term elasticity. This suggests that the country should put more effort into deploying modern clean energy to boost the long-term elasticity and further reduce carbon dioxide emissions.

The short-run environmental effect of lagged economic growth and population in Ethiopia was found to be significant and positive across the study period. Carbon dioxide emissions have a short-run elasticity of 0.546840 and 4.116509 with respect to lagged output growth and population, respectively. This means a 1% change in lagged output and population induces a 0.546840% and 4.116509% change in carbon dioxide emissions, respectively, when all other factors remain constant.

This suggests that output growth, population, and carbon emissions are directly correlated in the short term. Interestingly, the effect of output growth is outweighed by the elasticity of carbon dioxide emissions with respect to population, suggesting that population size contributes more to environmental deterioration than economic growth. This result is in line with Shafiei's (2013) earlier research findings.

There is little indication that economic growth and carbon dioxide emissions will soon decouple because the short-run output growth elasticity of carbon dioxide emissions is positive. However, a long-term decoupling may be shown by the long-term negligible impact of economic growth on environmental quality.

Interestingly, the study also found that the urbanization variable does not affect carbon dioxide emissions in the short or long run, which raises questions for future research to explore this dynamic further.

Economic Growth Equation of Ethiopia

To answer the second research question, the study also assessed an economic growth model, in addition to the environmental quality model investigation. Prior to estimating and discussing the specified economic growth equation, the researchers conducted pre-estimation tests such as unit root and co-integration analyses, just as they had done for the environmental quality model analysis.

4.1.6 Unit Root Testing

Table 5 below displays the indicators' stationarity behavior in the economic growth model. All indicators, with the exception of biomass energy use, are stationary at their first difference, according to the test results. This result made the ARDL model suitable for long-term co-integration analysis between the variables in the economic growth model.

Table 5. Unit Root Testing of the Economic Growth Equation variables

Variables	Augmented Dickey Fuller (ADF) and Phillps Perron (PP) Test		
	ADF T-statistics	PP T-statistics	Decision
lnCME	1.4644	1.5766	I(1)
D(lnCME)	-3.6920***	-3.8130***	
lnBE	-4.1908***	-8.3005***	I(0)
lnNRE	0.7038	0.8192	I(1)
D(lnNRE)	-4.7582***	-4.7582***	
lnGDPPC	2.009	1.7511	I(1)
D(lnGDPPC)	-4.1557***	-4.2076***	
lnK	-0.7791	-1.1817	I(1)
D(lnK)	-4.2336***	-7.5448***	
lnHK)	-0.4070	-0.1449	I(1)
D(lnHK)	-4.6299***	-4.6299***	

Note: *** indicate the significance of the test statistics at 1% level of significance.
(Sources: Own Estimation using Eviews 9.0)

4.1.7 Bound Co-integration Testing of Economic Growth Equation

After the stationarity aspects of the variables under inquiry have been established, the long-run association or co-integration between the model's indicators is investigated, much like the environmental quality model investigation. The growth model's long-run association outcome is shown in Table 6.

The table reveals that the F-statistic (5.619849) is highly statistically significant, indicating the presence of a long-run relationship among the variables in the economic growth model. This means the alternative hypothesis of long-run co-integration among the indicators is not rejected.

Table 6. Bounds Testing of the Economic Growth Equation

ARDL bounds testing result		
Null-hypothesis: No long run association among the model variables		
Test-statistics	Value	K
F-statistics	5.619849	5
Critical value bounds		
Significance	I0 Bound	I1 Bound
1 percent	3.41	4.68
2.5 percent	2.96	4.18
5 percent	2.62	3.79
10 percent	2.26	3.35

(Sources: own computation using EViews 9.0)

4.1.8 Model Diagnostic Testing of Economic Growth Equation

Before analyzing the long- and short-term elasticities of the economic growth equation, the model is first subjected to diagnostic tests.

Table 7 reveals the output of the diagnostic tests, and the test statistics cannot reject the null hypotheses presented for each test. This indicates that the diagnostic tests for serial correlation, heteroscedasticity, the Jarque-Bera test for normality, and functional form all show that the computed coefficients are independent of econometric issues, thus validating the overall findings of the study.

Table 7. Model Diagnostics Testing of Economic Growth Equation

Tests	Method	√F-statistics √Jarque-Bera for normality	P-value
Seral correlation	Breusch Godfrey LM	1.2046	0.3217
Heteroscedasticity	Breusch-Pagan Godfrey	0.3983	0.8926
Functional form	Ramsey Reset	2.7510	0.1128
Normality	Jarque-Bera	3.9055	0.1418

(Sources: own computation using EViews 9.0)

4.1.9 Model Stability Testing of Economic Growth Equation

As indicated in Appendix B, the stability test of the long-run coefficient of the economic growth model revealed the stability of the long-run coefficients, implying that they cannot affected by any significant changes over time.

4.1.10 Long-run and Short-run Estimates of Economic Growth Equation

Table 8 below depicts the long- and short-term elasticities of economic growth with respect to its explanatory variables.

Table 8. Long and Short-run Elasticities of the Economic Growth Equation

Dependent variable: Real gross domestic product per capita Model selected: ARDL (1, 0, 0, 1, 0, 0) Long-run coefficients				
Variables	Coefficients	Standard error	t-statistics	P-values
lnMCE	0.503853	0.115261	4.371429	0.0003***
lnBE	0.241128	0.425655	0.566486	0.5771
lnNRE	-0.104305	0.129726	-0.804045	0.4304
lnK	-0.142698	0.150111	-0.950616	0.3526
lnHK	0.063585	0.076620	0.829883	0.4159
C	-1.075321	4.789449	-0.224519	0.8245
Short-run coefficients				
D(lnMCE)	0.194435	0.075256	2.583669	0.0173**
D(lnBE)	0.093050	0.152194	0.611393	0.5475
D(lnNRE)	0.113614	0.060215	1.886797	0.0731*
D(lnK)	-0.055067	0.065944	-0.835051	0.4131
D(lnHK)	0.024537	0.032319	0.759230	0.4562
ECM-1	-0.385897	0.122787	-3.142806	0.0049***

Note: ***, **, and * statistical significance of the coefficients at 1%, 5%, and 10% levels of significance, respectively. (Sources: own computation using EViews 9.0)

The modern clean energy elasticity of economic growth is positive and statistically significant, amounting to 0.503853. This indicates a direct association between output growth and modern clean energy use. Specifically, if all other factors remain constant, a 1 percent increase in modern clean energy use would translate into a 0.503853 percent increase in output in Ethiopia. This result corroborates the findings of previous studies, such as Neuhaus (2016), Shafiei (2013), Pearson (2021), Soava *et al.* (2018), Bhattacharya *et al.* (2016), and Bozkurt & Destek (2015), which found that increasing modern clean energy use helps to raise a country's output growth over time.

Additional studies by Shahbaz *et al.* (2020) for a panel of 38 nations that consumed renewable energy between 1990 and 2018 and Apergis and Danuletiu (2014) for a panel of 80 countries also revealed results that demonstrated the significance of renewable energy for economic growth. Investing in renewables is essential to make economic growth sustainable, and economic growth is also very important for renewable energy investment, as these two variables are complementary. A nation can switch from conventional to modern clean energy when there is economic growth to meet the needed funds for renewables investment.

All other factors, however, are found to have negligible short-term effects on output growth. Ethiopia's output growth may be statistically explained by the short-run elasticity of output growth for modern clean energy and non-renewable energy use, which are 0.194435 and 0.113614, respectively. When all parameters are held equal, a 1 percent rise in modern clean energy and non-renewable energy use results in a 0.194435 percent and 0.113614 percent increase in Ethiopia's growth, respectively.

5 Conclusion and Recommendation

5.1 Conclusion

The study's findings suggest that non-renewable energy, as measured by gasoline, and biomass energy consumption have a negative environmental impact in Ethiopia in the medium and long term. These two energy sources are the primary cause of increased carbon dioxide emissions in the country. The study suggests that the large share of unclean or environmentally unfriendly energy in the total energy consumption mix and limited penetration of clean energy in Ethiopia may explain the detrimental impact of these energy sources on environmental quality.

These findings highlight the need for policymakers and stakeholders in Ethiopia to prioritize the adoption of clean energy sources to reduce carbon dioxide emissions and promote sustainable economic growth.

The study's conclusions indicate that modern clean energy sources like solar, wind, and hydroelectric electricity have a major and favorable impact on Ethiopia's environment. This indicates that these energy sources are essential for enhancing environmental quality by decreasing the anthropogenic levels of carbon dioxide emissions. The study recommends that policymakers and stakeholders in Ethiopia should focus on the implementation of modern clean energy sources to foster sustainable economic growth and mitigate carbon dioxide emissions.

From the economic growth model presented in the study, the utilization of modern clean energy has a statistically significant positive effect on Ethiopia's economic growth in both the short term and the long term. This is attributed to its ability to increase output and support sustainable economic development. Conversely, the use of non-renewable and biomass energy does not significantly contribute to the explanation of the country's economic growth. These findings further imply that policymakers and stakeholders in Ethiopia should prioritize the adoption of modern clean energy sources to encourage sustainable economic growth and development.

5.2 Recommendations

According to the findings of the study, contemporary clean energy plays a crucial role in fostering both economic development and environmental quality in Ethiopia. The research indicates that alternative modern clean energy sources could serve as a viable solution to the challenges posed by climate change, without jeopardizing Ethiopia's economic progress. These results underscore the significance of modern clean energy in the advancement of Ethiopia's green economy. By emphasizing the integration of modern clean energy sources, policymakers and stakeholders in Ethiopia can facilitate sustainable economic growth and development while simultaneously tackling environmental issues.

As a result, governments should implement effective support policies to encourage investment in modern clean energy capacity to achieve sustainable growth of clean energy use. The government should prioritize the development of environmentally friendly energy sources by increasing investment capital in modern clean energy for long-term green economy development. In Ethiopia, there is a need to invest more in greener energy choices such as wind, solar, and hydro. Ethiopia faces potential challenges in spreading renewable energy technologies and developing modern renewable energy sources. These challenges include high initial investment and development costs, user awareness issues, institutional and capacity issues, and international and regional challenges in developing hydro and other resources. To address these difficulties and improve the energy consumption structure, the national and local governments must coordinate and implement effective mechanisms. This will require devising strategies to increase user awareness, building institutional and capacity frameworks, and addressing international and regional challenges. There is a necessity for robust collaboration among the nation's policymakers, government entities, and international cooperation organizations to enhance investments in modern clean energy, with the goal of ensuring that future development is both environmentally and economically sustainable. By addressing these challenges, Ethiopia can foster sustainable economic growth and development while simultaneously tackling environmental issues.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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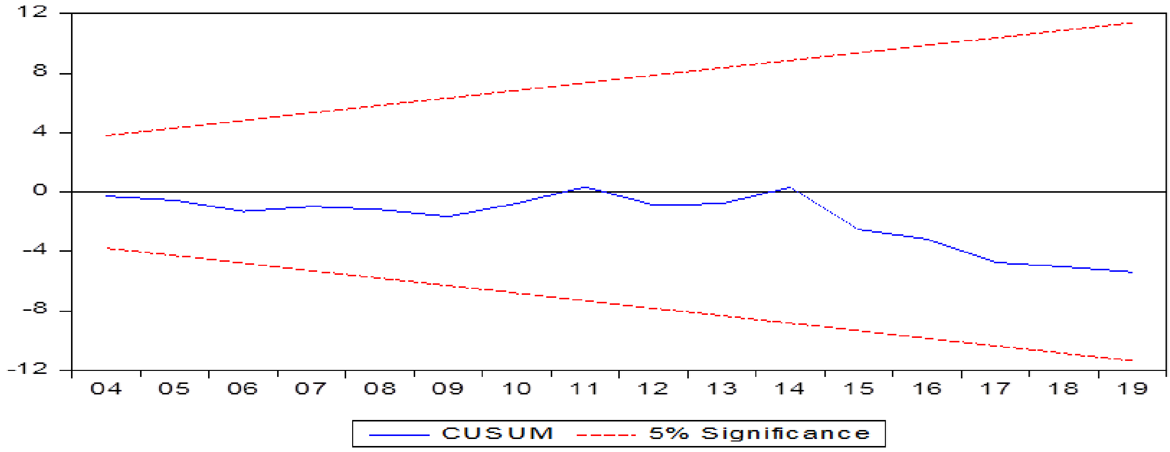
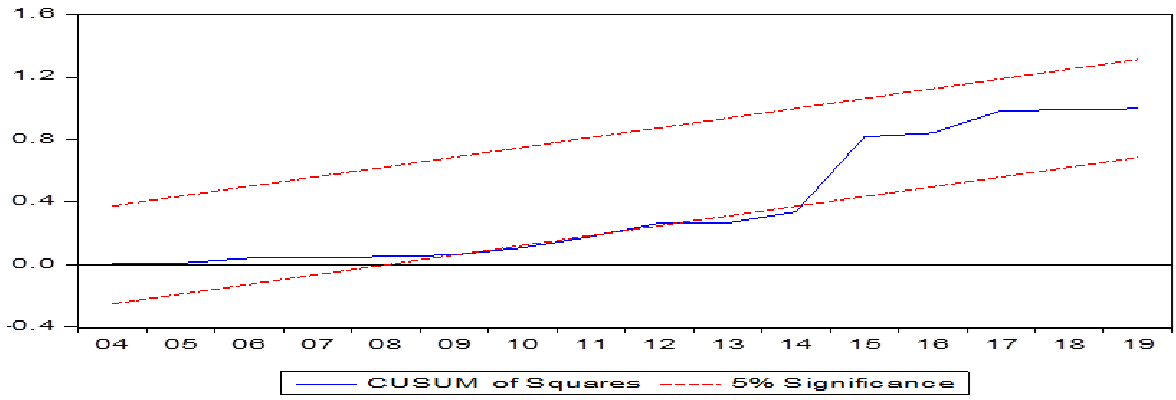
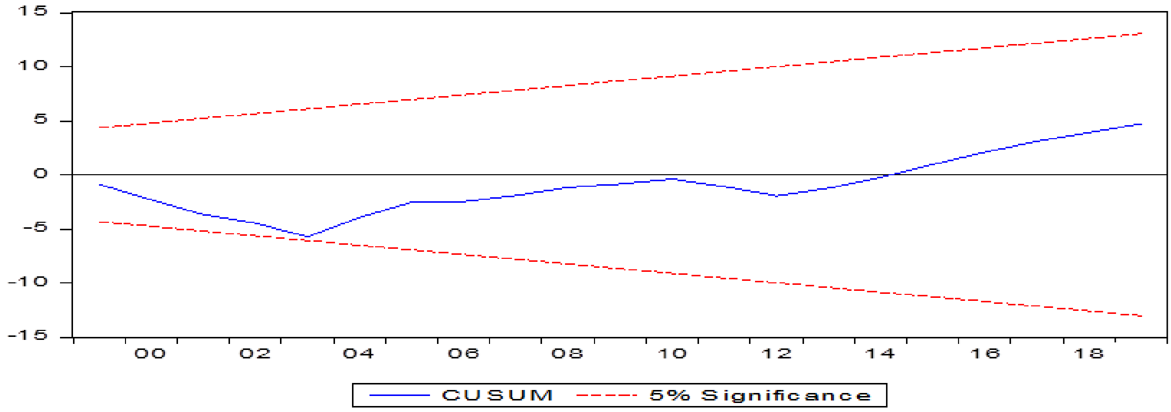
Appendices

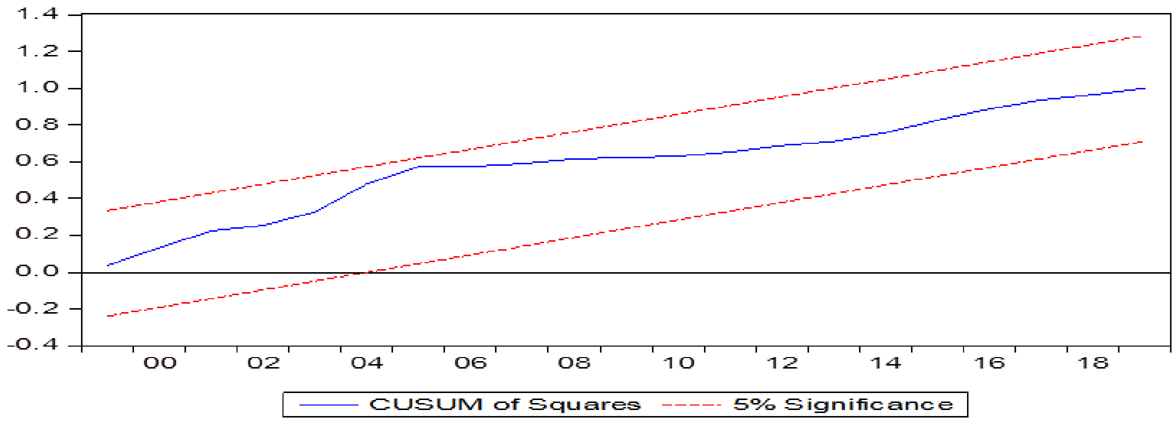
Appendix A: Plot of cumulative sum and cumulative sum of square testing of Environmental Quality Equation





Appendix B: Plot of cumulative sum and cumulative sum of square testing of Economic Growth Equation





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Morpho-physiological Response of Avocado (*Persea americana* Mill.) Seedlings to Different Salinity Levels in Sidam National Regional State, Southern Ethiopia

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Abstract

Salinity represents a primary environmental constraint that negatively impacts the morpho-physiological performance of avocado. As a result, this study was conducted to evaluate the response of avocado seedlings to different levels of salt stress. The experimental design was structured as a Randomized Complete Design (RCD) featuring four levels of salt concentration (0, 1.3 dS/m, 2.6 dS/m, and 3.9 dS/m) applied to grafted avocado seedlings, with three replications for each treatment. The avocado seedlings were cultivated from Ettinger avocado scions grafted onto Guatemalan race rootstock. The findings reveal that the majority of the morphological growth parameters, including rootstock diameter, sucker development, and root length, were significantly ($p<0.01$) influenced by the level of salt stress. In contrast, tap root diameter and lateral root length did not show significant ($p>0.05$) changes due to salt treatment. Notably, with the increase in salt concentrations from 0 to 3.9 dS/m, both the rootstock and scion diameters significantly decreased, along with the number of suckers developed on the rootstock. Additionally, significant ($p<0.01$) differences were noted in leaf length, bud count, leaf fresh weight and dry weight, leaf area, shoot height, taproot length, and lateral root length, all of which were significantly reduced as salt concentrations increased. Furthermore, photosynthesis, transpiration, stomatal conductance, and instantaneous water use efficiency were significantly impacted by salt concentration, with the highest values recorded at 0 and 1.3 dS/m. In general, salt concentration at 0 and 1.3 dS/m EC favors most of the growth and physiological performance of avocado seedlings compared to 2.6 and 3.9 dS/m. Thus, the study revealed that for vigorous growth of avocado seedlings at an early stage, the quality of irrigation water needs considerable attention to ensure robust avocado seedling growth.

Keywords/Phrases: Grafting, Photosynthesis, Rootstocks, Salt, Stress

1 Introduction

The avocado (*Persea americana* Mill.) is indigenous to Mexico and Central America, classified under the Lauraceae family, and ranks among the most economically significant tree crops globally (Silva and Ledesma, 2014). It offers numerous benefits, especially regarding its nutritional profile, being abundant in monounsaturated fatty acids (MUFA), dietary fiber, essential nutrients, and phytochemicals (Fulgoni *et al*., 2013). Additionally, it serves as shade trees, windbreaks, and ornamental plants (Albertin and Nair, 2004). Over the past century, it has been introduced to more than 50 countries worldwide, particularly in sub-tropical and tropical areas, with Ethiopia recognized as one of the leading avocado producers in tropical Africa.

Despite Ethiopia's long history of introduction and suitable agro-ecological conditions (Wayessa and

Berhanu, 2010), its distribution remains limited to a few areas (Derebe *et al.*, 2023; CSA 2014). However, in the last few years, with the development of Agro-Industry Parks and the emergence of direct fruit exports, the expansion to the central, southern, southwestern, and eastern parts of the country has improved. The Sidama region in the southern part of the country is known for its traditional coffee-enset-fruit-based agroforestry farming system (Asfaw and Lemenih, 2010) and is also where avocado was first introduced in the country (Derebe *et al.*, 2023; Megersa and Alemu, 2013).

Environmental stresses represent the primary constraints in harnessing the potential of horticultural crops globally (Celis *et al.*, 2018). Among these stresses, salinity, temperature, nutrition, light, oxygen availability, and metal ion concentration are the most critical factors. Salt stress is a significant adverse environmental factor that affects physiological processes by modifying the osmotic conditions within and surrounding the plant's environment (Jouyban, 2012). Elevated salt concentrations in the external solution of plant cells can lead to various consequences, which can be categorized into three distinct types: osmotic drought, toxicity resulting from excessive chloride and sodium retention, and nutritional imbalance (Karimi *et al.*, 2005).

To overcome these challenges, developing varieties that are tolerant to such stress conditions deserves considerable attention. Breeding for salt-tolerant varieties can help optimize the productivity of horticultural crops in areas affected by high soil salinity or saline irrigation water.

Saline irrigation water tolerance is an increasingly critical trait for avocado rootstocks, given the crop's high sensitivity to salt (Grieve *et al.*, 2012). Plants employ various mechanisms to withstand saline conditions, broadly categorized (Roy *et al.*, 2014) into three main types. These mechanisms are governed by long-range signals that inhibit shoot growth, commencing prior to significant Na+ accumulation in the shoots. The initial mechanism involves ion exclusion, wherein roots restrict the buildup of harmful Na+ and Cl– concentrations in the leaves. The subsequent mechanism is tissue tolerance, which is defined by increased salt concentrations in the leaves that are compartmentalized at both the cellular and intracellular levels, especially within vacuoles (Celis *et al.*, 2018; Reints *et al.*, 2020). The toxicity due to salinity increases Cl- and Na+ concentration. Mickelbart *et al.* (2007) identified that the "relative tolerance of the various rootstocks appeared due primarily to their ability to exclude Na+ and Cl- from the scion." They also reported that rootstock tolerance ability is indirectly observed from net CO2 assimilation, chlorophyll concentration, and leaf necrosis.

Mild water and salt stress improved intrinsic water use efficiency (iWUE = A/gs) by (i) decreasing gs through increased hydraulic resistance and osmotic adjustment, and (ii) decreasing A due to increased stomatal limitations rather than decreased photosynthetic capacity, according to Liao *et al.* (2022).

Furthermore, overall plant growth, net photosynthetic rate (PN), stomatal conductance (gs), transpiration rate (E), water use efficiency (WUE), and chlorophyll (chl) content are all significantly impacted by salinity, as shown by Musyimi *et al.* (2007). Avocado development and gas exchange are hampered by high salt concentrations.

Celis *et al.* (2018) also observed significant leaf burn in rootstocks grown in salt-treated soils. The occurrence of "tip-burn" on leaves in the autumn indicates excessive chloride uptake, leading to premature leaf drop during the winter months. Subsequent leaf regeneration can compromise flowering and fruit set, contributing to persistently low yields in certain orchards.

Rootstocks exhibit variability in their capacity to absorb and translocate chloride and sodium. Guatemalan rootstocks possess an intermediate level of salinity tolerance. However, comprehensive research on the comparative salinity tolerance of various avocado rootstock races remains limited. Therefore, evaluating the performance of avocado seedlings at an early developmental stage under varying salinity concentrations is crucial for determining the appropriate quality of irrigation water and soil media utilized in nurseries. In Ethiopia, data regarding the response of avocado seedlings to saline conditions are scarce. Consequently, this study investigates the morpho-physiological responses of grafted avocado seedlings to different salinity levels in the Sidama Region, Southern Ethiopia.

2 Materials and Methods

2.1 Description of the Study Area

The research was carried out between September 2021 and October 2022 at a site in the Dara district of Tafari-Kella, situated in the Sidama National Regional State (see Fig 1). This location is approximately 350 kilometers south of Addis Ababa, at an elevation of 1850 meters above sea level, positioned at a latitude of 6°30’0"N and a longitude of 38°24’0"E. The area receives an average annual rainfall of 1700 millimeters and has a typical temperature of 27 degrees Celsius. The prevalent agricultural system is characterized by coffee fruit cultivation, with avocado being the primary fruit crop.

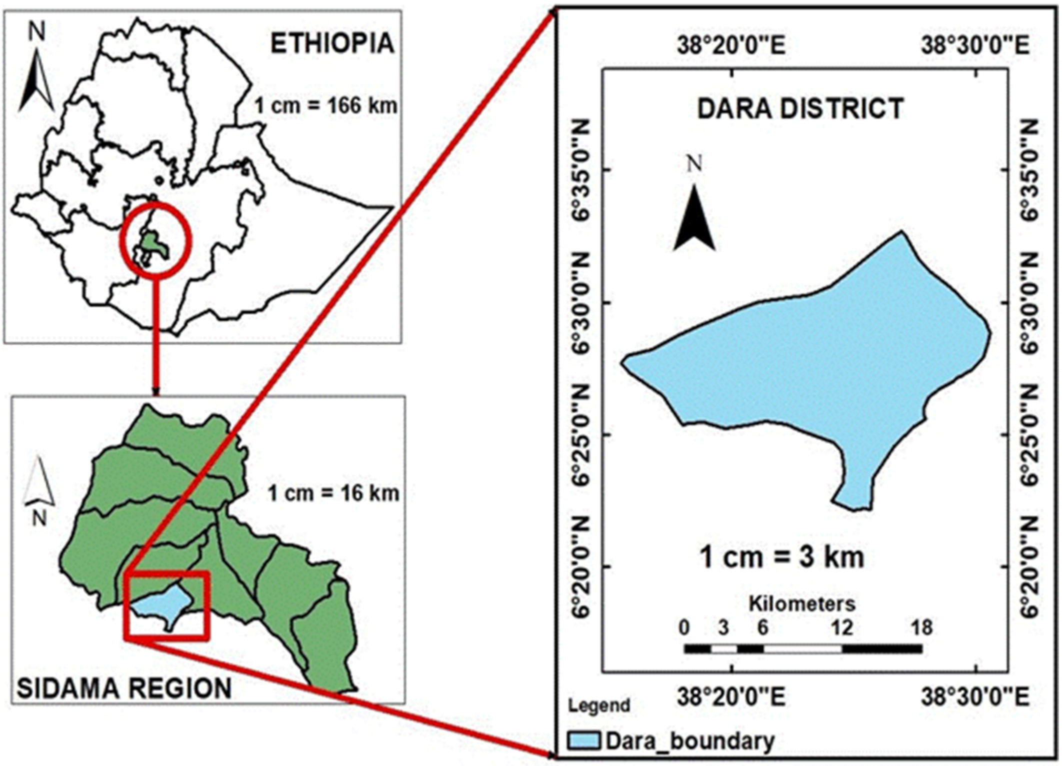

Figure 1. Map of the study area (Dara district Tafari- Kella kebele Sidama National Reginal State, Ethiopia)

2.2 Experimental Materials and Treatments

The avocado seedlings used as experimental material were obtained from Ethinger avocado scion grafted on Guatemalan race rootstock. The salt treatments were prepared from dissolved salt (*NaCl*) (Table 1) concentrations (1.3, 2.6, and 3.9 dS/m) dissolved in distilled water in separate containers to attain the respective salt concentration based on the following formula: Water Salinity in ECw (dS/m) x 640 = TDS (mg/l)

Table 1. List of salt treatment and its formulation from *NaCl*

Treatment	Salt level ds/m (ECw)	TDs (mg/l)	TDs (g/l)
1	0 ds/m	0 *NaCl* mg/l	0g/l
2	1.3ds/m	1.3x640 *NaCl* mg/l=832 mg/l	0.832g/l
3	2.6ds/m	2.6x640 *NaCl* mg/l=1664 *NaCl* mg/l	1.664g/l
4	3.9ds/m	3.9x640 *NaCl* mg/l=2496 mg/l	2.496g/l

PWhere: ECw=electrical conductivity of water, dS/m= deciSiemens per meter,
P mg/L=milligrams per liter and TDs=total dissolved salt

2.3 The Climatic Conditions of shade house

The maximum and minimum air temperatures for the shaded house were documented on five chosen days throughout the experimental period, utilizing the temperature and relative humidity data logger known as "testo". In that case, it was hung close to the seedling canopy. Accordingly, the mean maximum and minimum air temperature in the shade house was 11.7°C and 32.4°C, with a mean minimum and maximum relative humidity of 44.90% and 99.00%, respectively, at the time of the experiment.

2.4 Experimental Design

The experiment was carried out in a plastic shade using pots measuring 16 x 20 cm, which were filled with a composite soil made up of a 3:2:1 ratio of topsoil, compost, and sand, respectively. The study employed a Completely Randomised Design (CRD) with three replications. Each experimental unit consisted of four pots for each plot.

The four levels of salt treatments (0, 1.3, 2.6, and 3.9 dS/m) were applied after grafting throughout the growth period in the nursery. The treatments were applied once a week, while the pots were irrigated at two-day intervals throughout the experimental period to ensure available water in the root zone.

2.5 Data Collection

2.5.1 Characteristics of the Experimental Soil

A soil sample was taken from the mixed soil that was ready for planting in order to ascertain the physicochemical characteristics of the soil utilized for the experiment. Prior to laboratory analysis, the composite sample was dried and pulverized until it could fit through a 0.2 mm sieve. Following routine protocols at the Hawassa soil laboratory, the samples were examined for study-relevant parameters such pH, texture class, organic carbon, total nitrogen, accessible phosphorus, CEC, FC, and EC (Table 1).

2.5.2 Growth and morphological data

Growth and morphological data were collected from the aerial parts of the plant, such as rootstock diameter, number of suckers, scion diameter, leaf number, number of buds on scion, leaf length, grafted success, rootstock diameter, stem diameter, plant height, and scion diameter. The root system morphology was assessed by measuring root length and tap root diameter. Plant biomass was determined by quantifying leaf fresh weight, stem fresh weight, leaf dry weight, and root dry weight (all expressed in grams), as well as leaf area (cm2). Total fresh and dry weights were also recorded. All data were collected according to established methodologies, as detailed by Ndoro *et al*. (2018).

2.5.3 Stomata anatomy

One hundred twenty days after the therapy was administered, stomata anatomy was measured using the method suggested by Xu and Zhou (2008). An Automated Upright Leica Microscope DM5000 B with a 40x magnification lens fixed with a digital Leica DFC425/DFC425C image processing camera was used to investigate the stomata print. Stomata number (per mm^2), stomata cell number (per mm^2), stomata opening (μm), and stomata length (μm) were measured for every sample.

2.5.4 Gas exchange and physiological parameters

The third young and completely developed leaves of three randomly chosen seedlings were used to measure the following parameters: photosynthesis (A, μmol m^{-2} s^{-1}), transpiration rate (E), stomatal conductance (gs), and water usage efficiency. These measurements were made using a CIRAS-3 portable photosynthetic system (CIRAS-3 PP System Inc., Lincoln, NE, USA). The measurements were made 45 days after the completely grown, intact leaves were subjected to the actual moisture treatment.

A leaf surface area of 6.25 cm^2, ambient CO_2 concentration of 386 μmol mol^{-1}, leaf chamber mass flow rate of 251 μmol s^{-1}, atmospheric pressure of 840 bar, and manually fixed photosynthetic active radiation (PAR) at 600 μmol m^{-2} s^{-1} were all maintained during the measurements, which took place between 9:30 AM and 12:30 PM.

2.6 Statistical Analysis

ANOVA was performed on all morphological and physiological data in accordance with the General Linear Model (GLM) standard approach (Gomez and Gomez, 1984). SAS version 9.0 was used to conduct statistical analyses (SAS, 2008). Fisher's Least Significant Difference (LSD) test was used to differentiate treatment means at the 0.05 probability level.

3 Results and Discussions

3.1 Physico-Chemical Properties of the Experimental Soil

The physicochemical properties of the soil sampled from the experimental site are presented in Table 2. The results indicated that the soil has a sandy loam texture, with 75% sand, 20% silt, and 5% clay (Clingensmith *et al.*, 2022). Additionally, the soil has a medium CEC (33 Meq/100g soil), low EC (0.012 dS/m), 3.47% organic carbon, 10.8 ppm available phosphorus, and a slightly acidic pH of 6.5. These characteristics describe the composition of the soil media used for the pot experiment.

Table 2. Physico-chemical characteristics of the soils media composition used in the pot experiment

Soil properties	Values obtained
Sand%	75
Silt%	20
Clay%	5
Textural class	Loam sandy
pH	6.4
Organic Carbon (%)	3.56
Total Nitrogen (%)	0.19
Available Phosphorus (ppm)	10.9
Field Capacity (FC=v/v %)	31.72
CEC (meq/100g soil)	33
EC(ds/m)	0.012

3.2 Effect of salinity level on growth and Morphology of avocado seedlings

Salt stress levels had a statistically significant ($p<0.05$) impact on rootstock diameter and the number of suckers that grew on the rootstock, according to analysis of variance. Scion diameter, however, was not significantly impacted.

The rootstock diameter was significantly reduced as the concentration of salinity increased. Previous reports have confirmed that avocado plants subjected to higher concentrations of soil salinity experience significantly reduced vegetative growth compared to control conditions (Celis *et al.*, 2018). The maximum rootstock diameter (5.9 mm) was recorded from the control (0 dS/m) salt concentration, which was 21% greater than the treatment receiving the maximum salt concentration (3.9 dS/m).

On the other hand, the maximum number of suckers developed at the maximum salt stress level (3.9 dS/m), which was 70% more than the number of suckers developed on the control treatment (Table 3). This may be due to increased metabolic activity in the rootstock part compared to the scion part, as observed in similar studies by Rana and Bhatia (2004) and Lazare *et al.* (2021), in which a wide range of rootstock responses to salinity, including changes in circumference/diameter, were reported.

Consistent with these findings, Vazifeshenas *et al.* (2009) also reported that the number of suckers grown in pomegranate varied based on the genotype. Nevertheless, Table 3 shows that there was no discernible difference in scion diameter between the various salinity levels.

Table 3. Morphological Response of avocado seedlings to different salinity levels

Treatment Salinity level (ds/m)	Rootstock diameter (mm)	Scion diameter (mm)	No sucker growth (np^{-1})
Control	5.9^{a}	5.8	0.6^{c}
1.3	5.4^{b}	5.5	1.0^{b}
2.6	4.7^{c}	5.2	$1.5^{a}b$
3.9	4.3^{c}	5.0	2.0^{a}
LSD (p<0.05)	0.3	ns	0.7
CV (%)	3.94	8.72	29.5
P=value	0.006	0.31	0.01

Means with different letter with in the same column are significantly different at (p<.05)

3.3 Bud Number, Leave Number and Leaf length

The number of new buds, leaves, and leaf length developed per avocado scion were significantly influenced by the concentration of salinity (Table 4). The highest number of new buds per scion (3.06) was recorded from plants treated with 1.3 dS/m salinity level, while the minimum number of new buds (1.6) was recorded from plants receiving 3.9 dS/m (Table 4). As the salinity concentration increased, the number of new buds developed per scion was significantly reduced.

Salt concentration also significantly influenced the number of leaves developed on avocado scions. Plants exposed to 1.3 dS/m salinity level produced the highest number of leaves per scion, compared to those exposed to 3.9 dS/m salt concentration.

Similarly, different levels of salinity concentration in the growing media significantly influenced the leaf length per avocado scion. The longest leaf lengths of 5.4 cm and 5.3 cm were recorded from plants subjected to 1.3 dS/m and the control (0 dS/m), respectively (Table 4), while the minimum leaf length (2.3 cm) was recorded from plants subjected to 3.9 dS/m (Table 4). This suggests that as the salt concentration increased in the growing media, most of the growth parameters were significantly reduced.

The highest numbers of leaves were recorded from the 0 and 1.3 dS/m treatments, while the lowest numbers of buds on the rootstock were recorded from the rootstock receiving the maximum salt treatment (Table 3). This could be due to the low water uptake, leading to decreased stomatal conductance and other physiological activities, which resulted in reduced leaf growth. According to earlier research (Mandal *et al.*, 2012; Pampanna and Sulikeri, 1995), the maximum number of leaves may be the result of photosynthetic accumulation in recently grafted plants, which in turn boosted the number of nodes and the leaf primordia's ability to absorb moisture and nutrients.

Table 4. Effect of salinity level concentration on morphology of avocado (Guatemalan race) scion after grafted on seedling rootstock

Avocado (GT)	Parameter		
Treatment (Salinity level (ds/m)	Number of bud (np^{-1})	Leaf number (p^{-1})	Leave length (cm)
Control	3.04^{a}	$5.20^{a}b$	5.36^{a}
1.3	3.06^{a}	5.70^{a}	5.40^{a}
2.6	2.25^{b}	4.30^{b}	3.86^{b}
3.9	1.67^{c}	1.83^{C}	2.10^{b}
LSD (p<0.05)	0.76	1.37	1.08
CV (%)	11.58	18.14	15.1
p-Value	0.009	0.0001	0.002

Means with different letters within the same column are significantly different at ($p \leq 0.05$)

3.4 Stem diameter, plant height, scion diameter, and graft success

Salinity levels significantly impacted stem diameter, plant height, scion diameter, and grafted success percentage on the rootstock ($p < 0.05$). Plant height exhibited a significant negative correlation with increasing salinity concentration.

The 1.3 dS/m salt concentration produced the tallest plants (22.6 cm), followed by the control (0 dS/m) and 2.6 dS/m salinities (21.2 cm and 20.33 cm, respectively) (Table 5). The lowest plant height (18.33 cm) was recorded from seedlings that received the maximum salt concentration (3.9 dS/m). These results indicate that excess salt concentration poses adverse effects on plant growth and development.

Previous studies have revealed that plant growth is sensitive to saline conditions, and the level of sensitivity varies based on the species in higher plants (Bernstein *et al*., 2001). Avocado plants exposed to higher soil salinity levels also demonstrated a significant decrease in plant height, as confirmed by Berkessa (2020) and Bernstein *et al*. (2004). This could be due to a variety of physiological reactions, including altered ion balance, altered water status (water potential) both inside and outside the plant cell, mineral nutrition processes, and other aberrant metabolic processes.

Salinity-induced reductions in plant height are correlated with the accumulation of reactive oxygen species (ROS), which, at elevated concentrations, can be detrimental due to their high reactivity and potential to induce destructive processes and cellular damage (Kesawat *et al*., 2023). Prior research has established the role of rootstocks in modulating salt tolerance in grafted fruit trees, including avocado (Cooper, 1951; Haas, 1950). Concordantly, scion leaf production in avocado is inversely related to salinity levels (Oster and Arpaia, 1992), with the magnitude of growth reduction under stress varying among different rootstocks.

The effect of salinity was also observed on grafted success, where the highest grafted success (99.67%) was recorded from the control (0 dS/m), and 99.3% graft success was from 1.3 dS/m, followed by 43.3% and 25% graft success at 2.6 dS/m and 3.9 dS/m salinity levels, respectively (Table 4). Similar reports by Sibole *et al.* (2003) have revealed that plants subjected to salt stress decrease in growth, as it is directly associated with a reduction in photosynthetic capacity.

Table 5. Effect of salinity level concentration on morphology of avocado (Guatemalan race) scion after grafted on seedlings rootstock

Treatment	Parameter			
salinity level ds/m	Stem diameter (mm)	Plant height (cm)	Scion length (cm)	Grafted success (%)
Control	21.3	$21.1^{a}b$	11.6^{a}	99.6^{a}
1.3	22.0	22.6^{a}	11.6^{a}	99.3^{a}
2.6	21.1	$20.3^{a}b$	8.5^{b}	43.3^{b}
3.9	20.0	18.3^{b}	7.9^{c}	25.0^{c}
LSD (p<O.05)	3.3	2.6	0.7	1.2
CV (%)	8.9	7.5	9.61	2.8
P Value	0.1623	0.0194	0.0002	0.0019

3.5 Sucker development, Scion diameter and rootstock diameter

The highest scion diameter of 2.1 mm was recorded from the treatment that received 0 dS/m salt, and the minimum scion diameter was recorded in the 3.9 dS/m salt-treated seedling (Table 6). The plants that were treated with 3.9 dS/m salt had the most suckers (1.9 per plant), while the plants treated with 0 dS/m salt had the fewest suckers. This may be due to the increased metabolic activity in the rootstock as a result of stress hormone development under high salt concentration, which enhances the metabolic activities of stored food in the rootstock part.

The current results are consistent with those of Castro *et al.* (2009), Bhatia and Kumar (2011), and Rana and Bhatia (2004), who noted that rootstock diameter increased in response to salt stress. Conversely, Bonomelli *et al.* (2018) reported stimulated vegetative growth in avocado trees under low salinity conditions in Mexican plants, attributing this to enhanced cellular growth and increased cell number via osmoregulation. This observation is further supported by Penella *et al.* (2016), who demonstrated that salt stress significantly inhibited plant growth, resulting in a 40.6% reduction in leaf dry weight compared to control conditions.

Table 6. Effect of salinity concentration on morphology of avocado (Guatemalan race) after grafted on seedling rootstock

Avocado (GT)	Parameter		
Treatment Salinity level (ds/m)	Average sucker growth (np^{-1})	Scion diameter (mm)	Rootstock diameter (mm)
Control	1.10^{b}	2.17^{a}	$20.80^{a}b$
1.3	1.16^{b}	2.16^{a}	22.00^{a}
2.6	1.86^{a}	$1.60^{a}b$	16.00^{b}
3.9	1.96^{a}	1.45^{b}	15.33^{c}
LSD ($p \leq 0.05$)	0.5	0.59	1.6
CV (%)	17.85	16.2	4.58
P-Value	0.0145	0.0513	0.0001

Means with different letter with in the same column are significantly different at ($p \leq 0.05$)

3.6 Root number, Root length, and Tap and Lateral diameter

Among the root parameters considered, root number per plant was significantly ($p<0.05$) affected by salinity. However, root length, tap root diameter, and lateral root diameter were not significantly affected due to salt treatments (Table 7).

The control treatment had the greatest number of roots per plant (22.4), while the lowest number (9.9) was found at 3.9 dS/m. Additionally, it was noted that when saline levels rose, fewer roots were found (Table 7). Aydinsakir *et al.* (2015) also reported a similar outcome.

While root length, tap root diameter, and lateral root diameter did not exhibit statistically significant differences ($p>0.05$), root length showed an 18.9% increase, rising from 3.74 to 5.48 cm, with an increase in salt concentration from 0 to 3.9 dS/m. Conversely, tap root and lateral root diameters decreased from 4.9 to 3.9 mm and from 1.09 to 0.65 mm, respectively, as salt concentration increased from 0 to 3.9 dS/m (Table 7).

Table 7. Effect of salinity level solutions on root of avocado seedlings rootstock (Guatemalan race)

Treatment	Parameter			
Salinity level (ds/m)	Root number	Root length (cm)	Taproot diameter (mm)	Lateral root diameter (mm)
Control	22.44^{a}	3.74	4.94	1.09
1.3	16.11^{b}	4.15	4.20	1.00
2.6	11.33^{b}	4.44	4.40	0.77
3.9	9.97^{b}	5.48	3.90	0.65
LSD ($p \leq 0.05$)	6.3	Ns	ns	Ns
CV (%)	22.47	17.13	17.3	26.6
P-Value	0.0074	0.18	0.4	0.15

Means with different letter within the same column are significantly different at ($p \leq 0.05$)

Since roots are in close touch with the soil and take up water from it, while shoots provide water to the plant's aerial parts, it is well recognized that plant height and root length are the most significant salinity characteristics (Jamil and Rha, 2004). Usually, the main reaction to stress is the suppression of shoot and root development. Salinity has an impact on the growth, morphology, anatomy, and physiology of roots. Plant development may be affected by modifications in the roots' intake of water and ions, the synthesis of hormone signals that inform the shoot, and shifts in expression patterns (Bernstein *et al.* 2013).

3.7 Root, Leaf and Stem Fresh and Dry weight

Root fresh and dry weights were not substantially affected by salinity (Table 8). However, the fresh and dry weights of the leaves and stems varied significantly ($p<0.05$) as a result of the salt treatments.

Maximum leaf fresh (3.87 g) and dry (1.93 g) weights were observed at a salinity level of 1.3 dS/m, while minimum leaf fresh (0.63 g) and dry (0.23 g) weights were recorded at 3.9 dS/m.Stem fresh (7.24 g) and dry (3.62 g) weights were highest at 0 dS/m. The lowest stem fresh (3.57 g) and dry (1.82 g) weights were recorded at 3.9 dS/m, representing a decrease of 40% and 33%, respectively, as salinity increased from 0 to 3.9 dS/m (Table 8).

The findings suggest that excessive salinity may hinder growth by delaying the plant's absorption of water, which could be the cause of the decline (Werner and Finkelstein, 1995). According to Neumann (1997), salinity can quickly impede stem growth and, consequently, the ability to absorb water and vital mineral nutrients from the soil.

Similar results were reported by Dolo (2018), who found that salt stress dramatically reduces the fresh and dry weights of leaves as well as the dry weights of roots and stems. Similarly, Musyimi *et al.* (2007) found that high saline concentrations significantly decreased the fresh and dry weight production of both shoots and roots. The reduction in leaf number and the formation of smaller leaves as a result of the growth medium's increased salinity were cited as the causes of the drop in leaf fresh weight. The fresh weight of the roots, aerial parts (leaves and stems), and the total plant in control treatments (leaf fresh weight and stem fresh weight) were consistently and considerably higher than those that received saline irrigation, according to Bonomelli *et al.* (2018).

Table 8. Effect of salinity level solutions on fresh weight (shoot and root) of avocado seedlings rootstock (Guatemalan race)

Treatment Salinity (ds/m)	Parameter					
	Root fresh weight (g plant^{-1})	Root Dry weight (g plant^{-1})	Leave fresh weight (g plant^{-1})	Leaf dry weight (g plant^{-1})	Stem fresh weight (g plant^{-1})	Stem dry weight (g plant^{-1})
Control	5.48	2.76	2.86^{b}	1.46^{b}	7.24^{a}	3.62^{a}
1.3	4.44	2.57	3.87^{a}	1.93^{a}	6.69^{a}	$3.33^{a}b$
2.6	4.15	1.93	0.67^{c}	0.29^{c}	3.92^{b}	1.92^{b}
3.9	3.74	1.75	0.63^{c}	0.23^{c}	3.57^{b}	1.82^{b}
LSD ($p\leq0.05$)	Ns	NS	0.21	0.55	2.06	1.541
CV (%)	19.18	21.98	13.80	23.56	23.08	22.21
P-value	0.1826	0.09	0.0001	0.001	0.022	0.009

Means with different letter within the same column are significantly different at ($p<0.05$)

3.8 Leaf Area, Total Fresh weight and Total dry weight

Salt stress had a substantial impact on leaf area, total fresh weight, and total dry weight ($p < 0.05$). At a salinity level of 0 dS/m, the largest leaf area measured was 874.29 cm2, and at 3.9 dS/m, the smallest leaf area measured was 159.19 cm² (Table 9). As salinity levels increased, leaf area showed a decrease of approximately 81.8%, dropping from 0 to 3.9

dS/m.

High salinity inhibits cell elongation in actively growing tissues, which in turn affects leaf area and dry matter assimilation in the plant. This is the reason for the decrease in leaf area that occurs when salinity levels rise (Aydinsakir *et al.*, 2015; Hasanuzzaman *et al.*, 2013).

In parallel, the highest total fresh weight was observed at 15.59 g and the highest dry weight at 7.85 g at the control level (0 dS/m). Conversely, the lowest total fresh weight (7.63 g) and dry weight (3.63 g) were noted at the maximum salt stress level of 3.9 dS/m. Similarly, Bonomelli *et al.* (2018) reported that cumulative leaf area, fresh weight, and dry weight increase as the level of salt stress decreases.

Table 9. Effect of salinity level solutions on total leaf area, fresh and dry weight of avocado seedlings rootstock (Guatemalan race)

Treatments salinity level (ds/m)	Leaf area (cm^2)	Total fresh weight (g $plant^{-1}$)	Total dry weight (g $plant^{-1}$)
Control	874.29^a	15.59^a	7.85^a
1.3	608.70^b	15.08^a	7.83^a
2.6	214.82^c	8.02^b	3.83^b
3.9	159.19^c	7.63^b	3.69^b
LSD ($p \leq 0.05$)	185.3	4.2	4.02
CV (%)	21.2	19.3	17.9
P value	0.013	0.03	0.01

Means with different letter with in the same column are significantly different at ($p \leq 0.05$)

3.9 Stomata number, length and width

Levels of salt stress had a substantial ($p<0.05$) impact on stomata number, length, and width. While the maximum stomata length (0.35 mm) and width (0.32 mm) were observed at 1.3 dS/m, which were statistically equivalent to 0 dS/m, the greatest stomata number (22/mm2) was reported at 0 dS/m.

The majority of the stomata metrics, such as stomata number, length, and width, reduced by 25%, 23.6%, and 13.3%, respectively, when the salt concentration rose from 0 to 3.9 dS/m (Table 10). Aydinsakir *et al.* (2015) also reported similar findings, indicating that the number of stomata dropped as saline levels increased.

Water and salt stress decreased stomatal length (SL), width, perimeter, and area (amax), as well as stomatal density (SD), according to similar findings reported by Xue *et al.* (2021). Guo *et al.* (2018) found that salt stress significantly reduced the stomatal density, stomatal width, stomatal area, and stomatal area index in tomato cultivars.

Table 10. Physiological Response of seedling avocado rootstocks to different salinity level

Treatment Salinity level (ds/m)	Stomata number (per mm^2)	Stomata length (μm)	Stomata Width (μm)
0	22.0^a	0.34^a	0.28^ab
1.3	18.6^b	0.35^a	0.32^a
2.6	15.3^c	0.24^b	0.22^b
3.9	13.6^c	0.21^c	0.21^b
LSD ($p \leq 0.05$)	2.1	0.08	4.13
CV (%)	6.46	15.73	8.61
P value	0.0001	0.008	0.002

Means with different letter within the same column are significantly different at ($p \leq 0.05$)

3.10 Photosynthesis, Transpiration, Stomata conductance and Instantaneous water use efficiency (IWI)

Salt treatments had a substantial (P<0.05) impact on physiological measures like photosynthetic rate, transpiration, gas exchange (gs), and water use efficiency (Table 11). As the salt level rose from 0 to 3.9 dS/m, the transpiration rate decreased by 60%; Aydinsakir *et al.* (2015) found a similar finding.

Similarly, when salt levels rose from 0 to 3.9 dS/m, the photosynthetic rate dropped by 51.8%. Additionally, Hnilickova *et al.* (2021) revealed that stomatal conductance decreased concurrently with an increase in CO2 absorption when the concentration of NaCl reached 100 mM (A). Stomatal closure (gas) and/or other non-stomatal constraints, such as disruption of the photosynthetic electron chain and inhibition of Calvin cycle enzymes, can cause the rate of photosynthesis to decrease (Chaves *et al.*, 2009). While proper control of the photosynthetic process can reduce the generation of reactive oxygen species (ROS) in photosystem II (PS2) and the reducing side of photosystem I (PS1), a decrease in gas exchange can assist prevent excessive water loss through transpiration (Asada, 1999).

Similarly, research by Musyimi *et al.* (2007) has demonstrated that in plants treated with salt, a decrease in stomatal conductance (gs) is correlated with a decrease in net photosynthesis brought on by rising salinity. Although stomatal conductance is the main cause of the decrease in photosynthesis in salt-treated plants, non-stomatal variables also have a role (Ashraf, 2002; Netondo *et al.*, 2004). Stomatal conductance is a more accurate early indication of salt stress in avocados than studies of leaf water content, leaf water potential, or other growth indicators, according to Schaffer and Whiley (2003).

According to Redondo-Gómez *et al.* (2007), after six days of treatment, the net photosynthetic rate (A) dramatically decreased as external salinity increased. According to Guo *et al.* (2018), the avocado cultivars they utilized in their study showed slight decreases in net photosynthetic rates (Pn), stomatal conductance (gs), and transpiration rates (Tr) under NaCl stress. Similar findings were also documented in mature avocado trees that were irrigated with an EC = 1.5 dS/m salinity level (Acosta-Rangel *et al.*, 2019). The avocado leaves that were clearly harmed by the salinity—referred to as partially burned leaves—experienced photoinhibition, a decrease in photosynthetic rate, and a decrease in water-use efficiency. These findings suggest that the poor performance in carbon assimilation contributed to decreased yield and increased mortality.

Table 11. Response of avocado seedlings rootstock (Guatemalan race) to different physiological growth parameter under different salinity level

Avocado (GT)	Parameter			
Treatment salinity level (ds/m)	Photosynthesis rate (μm)	Transpiration rate (E: mmol/mol)	Stomata conductance (gs: mmol)	IWUE
Control	5.40^{a}	3.05^{a}	116.6	2.84^{a}
1.3	4.63^{a}b	2.72^{a}b	110.6	2.75^{a}
2.6	3.96^{a}b	2.26^{a}b	71.6	2.35^{a}b
3.9	2.60^{b}	1.29^{b}	57.6	1.48^{b}
LSD (p≤0.05)	2.2	1.2	61	1.19
CV (%)	23.8	27.7	30.5	23.2
P value	0.04	0.04	0.07	0.05

Means with different letters within the same column are significantly different at (p<0.05)

4 Conclusion and Recommendation

Ethiopia's agroecological conditions favor the cultivation of different fruit crops of tropical, subtropical, and temperate zone origins. Nevertheless, a variety of biotic and abiotic stress conditions affect these crops. Salinity is one of the environmental factors that negatively impacts development, physiology, and yielding potential among abiotic stresses. The avocado plant is particularly vulnerable to this kind of stress that is common in subtropical regions. Nevertheless, the performance of avocado seedlings under such stress conditions has not been extensively studied.

The study indicated that salt stress impairs the morphological and physiological performance of grafted avocado seedlings. As the salinity level increases, both rootstock and scion diameter, as well as the grafting success percentage, were substantially decreased compared to the salt-free treatment. The majority of the vegetative development metrics declined as the salt concentration rose from 0 to 3.9 dS/m, with the exception of the number of suckers on the root section, which exhibits an increasing tendency. The number of buds, number of leaves, length of leaves, stem diameter, plant height, scion length, and diameter of the scion and rootstock are some of these factors.

Both the shoot and root portions of avocado seedlings produced much less fresh and dry weight when grown in high saline environments. In comparison to the treatments with saline circumstances, the aerial component (leaves and stems) and underground root parts' observed fresh and dry weights were significantly higher in the stress-free treatments.

Avocado seedlings treated with higher salinity levels significantly reduced stomata (number, length, and width), stomatal conductance, and photosynthetic rate. The control treatment without salt growing conditions significantly increased all growth and physiological parameters compared to the salt stress conditions.

The irrigation water with an EC of <1.3 dS/m positively affected both vegetative growth and physiological performance, while salinity levels >1.3 dS/m negatively affected most of the morpho-physiological performance of avocado seedlings. Therefore, considerable attention should be given to the irrigation water quality for avocado seedling production at nursery sites to ensure the development of vigorous seedlings.

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Changes in soil physicochemical properties and nutrient dynamics under liming acid soils

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Abstract

Area specific investigation of impacts derived from liming acid soils and the consequent effects on plant nutrient bioavailability and soil physicochemical properties is important. This work aimed at investigating dynamics of nutrient bioavailability and changes in soil physicochemical properties under liming acid soils in the west Wallaga zone of western Ethiopian high rainfall regions. Lime requirements were calculated for all soil samples using the acid saturation procedure. Then, important physicochemical properties of the soils and bioavailability of nutrients were determined following standard procedures. The highest changes observed as a result of liming were 36.59 to 37.19 cmol Kg^{-1} for CEC, 0.97% to 0.47% for SOC, 1.76 to 1.40 g cm^{-3} for bulk density, 30.31 to 37.21% for porosity, 30.25 to 34.55 μS cm^{-1} for EC, 2.56 to 0.26 cmol $Kg^{-1}$for EA, and 0.08 to 0.02% for TN. This is attributed to the relatively higher CEC of clayey soils. It was observed that liming conditions, CEC, EC, EA, SOM, TN, and AP have significant ($p < 0.001$) correlations amongst themselves and with some other soil physicochemical properties such as porosity, bulk density, and C/N ratio. Bioavailability of P, N, S, Ca, K, and Mg were significantly positively ($p < 0.01$) enhanced by liming. This is due to improved mineralization of organic compounds, solubilization of some K, Ca, and Mg compounds, and input of Ca and Mg through liming. More research may be necessary to create a further understanding of the long-term effects of liming acidic soils on innate sources of nutrients and biological properties.

Keywords/Phrases: Acid soil, Effect of liming, Nutrient bioavailability, Physicochemical properties

1 Introduction

These days, soil acidity is one of the main challenges in crop productivity in the high-rainfall regions of the world. Globally, soil acidity is expanding and causing more than half of the globally available arable lands are increasingly less productive (Kochian*et al*., 2015; Holland *et al*., 2018; Opala *et al*., 2018). Particularly in humid tropics and sub-tropics, basic cations are leached by long-term rainfall and gradually replaced by iron or aluminum cations. This aggravates soil acidity (Fekadu *et al*., 2021). Besides this natural phenomenon, other human-induced causes such as deforestation, cultivation of soils potentially containing acidic sulphate, removing all harvested plant materials, and excessive application of ammonium-based fertilizers cause soil acidity (Mekonnen *et al*., 2020).

Soil acidity changes the proportions of macronutrients and micronutrients in the soil, and this, in turn, leads to a deficiency of some macronutrients while micronutrients become available in large quantities that could cause toxicity to plants (Abdulkadir *et al*., 2014). Soil acidity also causes abnormal plant growth and inefficient water use (Holland *et al*., 2018). At higher levels, aluminum affects phosphorus availability and absorption by plants by fixing it into insoluble oxides. In addition, it affects several biochemical processes which are important for general plant growth. It also causes plant roots to have a flabby appearance by shortening and inflaming them Opala *et al*., 2018).

In Ethiopia, particularly in the high-rainfall western and southwestern highlands, soil acidity is increasingly becoming a severe menace to crop production (Achalu*et al.*, 2021; Abdena, 2013; Wakshuma*et al.*, 2019). As some studies indicated, about half of arable lands are becoming acidic in Ethiopia (Tamene *et al.*, 2017; Eyasu, 2016). What worsens soil acidity is that it is closely related to Al^{3+} toxicity, which in turn affects plant production. This leads to low soil fertility and high H^{+} and Al^{3+} toxicity, which in turn leads to low crop production and unsustainable agricultural production in general in the western and southwestern high-rainfall regions of Ethiopia. Especially in the west Wallaga zone of the Oromia region, even though excess natural and synthetic fertilizers have been applied, soil productivity and plant production have been decreasing from time to time (Abdena, 2013; Wakshuma*et al.*, 2019).

The main causes of severe soil acidity in the western high rainfall region, particularly the west Wallaga zone, are high rainfall, severe soil erosion, deforestation, cultivation of potentially acid sulphate soils, removing all harvested plant materials Achalu*et al.*, 2012;Abdena, 2013). Similarly, Legesse *et al.* (2013) reported that there are high concentrations of Al^{3+} and Fe^{3+} oxides in western Wallaga soil, and this brings significant P-fixing problems.

Currently, several management options are being tried in Ethiopia to alleviate soil acidity and reduce its severe effect on agricultural production. Among the management options, lime application, and organic amendments, including the application of farmyard manure, crop husks, and compost, are mentioned (FAO, 2017; Habtamu, 2015; Fekadu *et al.*, 2014). However, for severe soil acidity amelioration, aggressive liming is the best management option since it has a relatively higher capacity to neutralize the acid and reduce Al^{3+} toxicity. However, few works were done to investigate the holistic effects of liming acid soils in the highly acidic soils of West Wallaga. The main aim of this work was to investigate the impacts of liming acid soils on physicochemical properties, plant nutrients bioavailability, and lime requirements in soils of Nedjo and BodjiDirmaji Districts, Western Wallaga Zone, Oromia Region.

2 Materials and Methods

2.1 Sampling Areas

Samples were collected from six areas of BodjiDirmaji and Nedjo districts of western high rainfall region of Ethiopia, located at around 480 - 590 Km from Addis Ababa to the west. Purposively six locations - BikiltuDilla (BD), KutallaBildimma (KB), AmumaAgalo (AA), KoteGennasi (KG), NasisGennasi (NG) and WalitateGidda (WG) – were selected. These sampling areas are specifically soil acidity-affected areas and found between latitude of 09^{o}25’33” and 09^{o}33’16” N and longitude of 35^{o}24’32” and 35^{o}36’28” E. The vernacular name of the soil in the area is “Biyyo Dima”,which means red soil. The soil of this region is highly acidic, and its fertility is very low. These areas are part of tropical and subtropical high-rainfall regions. Soils of West Wallaga in general and those of the study areas in particular are characterized by high P-fixing capacity, high content of Fe oxides, strongly structured and low-activity clays, and soils with these properties are most likely classified as Nitisols according to WRB soil classification system (EthioSIS, 2014). The natural vegetation of the area ranges from tropical rainforests to desert savannas. Several cereal crops, oil crops, pulses coffee, and fruits are produced in the regions.

2.2 Sampling procedure

The random sampling strategy was followed to take a total of eighteen (triplicate) surface soil samples (0-35 cm) to assume topsoil depth, and 6 kg each were collected. The total area coverage of the sampling sites was about 300 hectares from the two districts. The samples were collected from farmlands to determine lime requirement, nutrient availability, and physicochemical analysis. For bulk density measurement, eighteen core samples were collected. For moisture analysis, eighteen composite cane samples were collected. After bringing it to the soil laboratory, about 1.0 kg of soil was taken from each sample and dried in open air, then ground and sieved using 0.25 mm mesh. The prepared samples were kept in labeled sample holders for physicochemical analysis. For greenhouse experiments and control experiments, 1 kg and 3 kg samples were arranged for liming experiments in greenhouse incubation pots in a randomized complete block design.

2.3 Instruments, reagents, and chemicals used

Analytical-grade reagents and chemicals were used throughout the study. These include sodium hydroxide solutions ($NaOH$), 10 N, concentrated H_2SO_4, and saturated boric acid solution (H_3BO_3) for nitrogen determination using the Kjeldahl procedure. Ammonium acetate Solution (1 NNH_4OAc), for extraction of Ca, Mg, and K; 0.005 M EDTA (Ethylenediamine tetra acetic acid), 6 N hydrochloric acid (HCl), 0.1 M TEA (Triethanolamine), 0.1 $MCaCl_2$ (calcium chloride) for extraction of micronutrient cations (Fe, Zn, Mn, Cu) and $HNO_3 - HClO_4$ di-acid mixture for digestion of samples for micronutrients determination; 2 $\%NaCN$ (Sodium cynide) to prevent interference of Fe, Zn, Mn, Cu while measuring Ca and Mg with atomic absorption spectrophotometer (AAS). Hydrochloric acid (HCl), 0.05 N for boron (B) determination; 0.4 $NK_2Cr_2O_7$ solution (2:1) H_2SO_4: H_3PO_4 mixture, mercury (II) oxide (HgO), phenalthroline indicator and 0.2 N ferrous ammonium sulfate for determination of carbon were used. Standard stock solutions of all elements to develop a calibration curve for each element. Regarding instruments, cations such as Mg, Ca, Zn, Fe, Cu, Mn, and Mo were determined by AAS. Flame atomic photometer (FAAS) was used for the determination of K; Uv-Vis was used spectrophotometer for the determination of B, P.

2.4 Physicochemical analysis of the soils

Standard procedures were followed to measure some important physical and chemical characteristics of the soils. Thus, the pH values of the soils were determined by using combined-glass electrodes in H_2O and 0.01M $CaCl_2$ suspension before and after lime application. Neutral 1N potassium chloride was used to leach hydrogen and aluminum ions from the soil and exchangeable acidity by titrating the acidity brought into solution with a standard solution of 0.02M $NaOH$ (Van Reeuwijk, 1992). Again, this was done before and after the lime application. Organic matter was determined by using the Walkely and Black methods. The CEC of the soils was determined by the ammonium acetate method and electrical conductivity (EC) (1:1 H_2O) by following the methods described by Rowell (Van Reeuwijk, 1992). The cations such as Na and K were determined using FAAS, Ca, Mg, Cu, Fe, Mn, and Zn were analyzed using AAS after being extracted using 1N Ammonium acetate (NH_4 OAC at pH 7). The available form of P was determined following Bray I (Bray and Kurtz, 1945), Mehlich 3-P (Mehlich, 1984), Olsen method (Olsen and Sommers, 1982), and $CaCl_2$ extraction methods depending on soil pH results.

2.5 Determination of lime requirement

Lime requirement (LR) of each soil was estimated with the acid saturation method to predict the amount of lime material to be added to every soil to reach target pH values of 5.4, 6.0, and 7.4. This method was chosen for its relatively simple laboratory procedures. These target pH values are within the optimum pH ranges for the growth of many crops, and this is why they were chosen as target pH values (Bouman *et al.*, 1995; Brown *et al.*, 2008).

In the acid saturation method, exchangeable acidity (Ex.Ac), effective cation exchange capacity (ECEC), and permissible acid saturation (PAS) were used to determine the quantity of the lime material to be added. Then, the LR was computed as follows (Manson and Katusic, 1997):

$$LR = LRF[EX.Ac - (ECEC * PAS)] \quad (1)$$

where, LR = Lime requirement (kg ha^{-1}); LRF is the lime requirement factor (kg lime ha-1) to lower the exchangeable acidity by 1cmol. The accepted value of LRF is 3000 kg lime ha^{-1}cmol^{-1} for most Ethiopian soils (Farina 1991; Sertsu& Bekele, 2000); Ex. Ac = exchangeable acidity ($[Al^{3+}] + [H^{+}]$); PAS is permissible acid saturation, and its value is 20% for maize (Manson *et al.*, 2004), and ECEC is effective cation exchange capacity (Exchangeable acidity + Exchangeable bases).

Calcium carbonate ($CaCO_3$) powder was used as liming material. For each target pH value, the quantities of $CaCO_3$ ha^{-1} (in mmolc) added were computed, and the field level was expressed in kg of equivalent $CaCO_3$ ha^{-1}. Then, from each sample, 4 kg of soil was taken into pots and incubated with three levels of liming. The soils in the incubating pots were carefully mixed, and water was supplied until field capacity (30 kPa) was attained. Replicate treatments were made for all samples. Totally, 54 pots (6 soils x 3 lime levels 3 replicates) were arranged in a completely randomized design (CRD) in an illuminated greenhouse.

The soils were incubated in the greenhouse for four months until the targeted *pH* values (5.5, 6.5, and 7.2) reached *pH* by both *pH* (H_2O) and *pH* (KCl) methods. Four-month incubation was chosen, which corresponds to one growing season of the most common crops. All-important parameters were determined before and after liming and incubation.

2.6 Instrument calibration and method validation

All the instruments AAS, Uv-Vis, FAAS, and procedures were calibrated by recovery tests for each plant nutrient. Thus, the efficiency of the methods was tested by spiking each sample with a known concentration (< 10%) of each nutrient into the number of samples to be analyzed. For *Fe* and *Mn* 0.5 mg L^{-1}, for *B*, *Cu*, *Mo*, and *Zn* 0.05 mg L^{-1}, for *Ca*, *Mg*, and *K*, for *P* and *N* 0.5 mg, L^{-1} were added to the weighed amount of sample prepared for extraction. After measurement, percentage recovery was calculated for each method by subtracting the amount before the spike from the amount after the spike, dividing the difference by the amount spiked, and then multiplying by 100. The detection limits of the methods were tested by seven blank samples in the same procedure in which the samples were treated. Standard deviations of the readings from the seven blanks were multiplied by 3 to obtain the detection limit of the methods. Then, calibration curves were prepared for each element within the detection limits of the methods. The instruments were calibrated by measuring all parameters in non-spiked and spiked soil samples to check the consistency and effectiveness of the measuring instruments and processes. To obtain the best working procedure, all working conditions were optimized. Then, optimum conditions were used for the next nutrient determination (Houba*et al.*, 1989).

Statistical data analysis

A one-way analysis of variance (ANOVA) was used to assess the effects of liming on soil-selected chemical properties and plant nutrient availability. The $F-test$was used to check whether there was a significant difference among the means. The level of correlations among soil properties was determined using simple correlation analysis. The SAS software package (SAS 2004). SASVR 9.1; Cary, NC) was used for statistical analysis.

3 Results and Discussions

3.1 Variation in *pH* and LR values

The LR values of the soils were dependent on the level of soil acidity and *pH* values, as shown in Table 1.

Table 1. *pH* and LR values of the six soils (Kg$CaCO_3$ ha^{-1})

Soils	*pH* of Soils	Target *pH* Values		
		5.4	6.0	7.4
		LR (Kg $CaCO_3$ ha^{-1})		
AA	4.72	4224	6282	7983
BD	4.54	4344	6541	8660
KB	4.46	4881	6683	8786
KG	5.21	3808	5870	6879
NG	4.97	4115	6164	7569
WG	5.14	3980	5642	6693

Note: AA= AmumaAgalo sample site; BD= BikiltuDilla sample site; KB= KutallaBildimma sample site; KG= KoteGennasi sample site; NG= NasisiGenasi sample site; WG= Walitate Gida sample site

The required amount of lime (kg $CaCO_3$ ha^{-1}) to increase the soil *pH* to target values of 5.4, 6.0, and 7.4 ranged from 3808 to 4881; 5642 to 6741 and 6693 to 8786 kg $CaCO_3$ ha^{-1},respectively for the six soils. The LR values of the soils corresponded to the levels of the Ex.Ac. The highest Ex.Ac (2.98 cmolc kg^{-1}) and LR values were that of KB soil. This result shows that the level of Ex.Ac in a soil determines its LR level.

3.2 Soil physicochemical properties as affected by liming

Variations in pH levels and liming have substantial (p <0.01) impacts on all the soil physicochemical properties investigated except the *C*:*N* ratio (Table 2). As a result of liming, the highest change in CEC (36.59 to 37.19 cmol kg^{-1}), SO*C* (0.97 to 0.47%), EC (30.25 to 34.55 μS cm^{-1}), EA (2.56 to 0.26 cmol kg^{-1}) and T*N* (0.02 to 0.08%), A*P* (1.76 to 6.79 mg kg^{-1}), were observed in the BikiltuDilla soil with clay textural class. This is because clayey soil usually has relatively greater CEC, the key soil property that plays a major role in amending soil physicochemical properties. Therefore, the effect of liming acid soils largely correlates to the CEC of the soils, which in turn depends on soil textural class. The T*N* contents were positively significantly (p< 0.01) changed by the addition of lime to all of the six soils. This is because nitrogen mineralization is enhanced when lime is added to acid soil (FAO, 2017).

In addition, the application of lime increases the *pH*, consequently, nitrogen-fixing bacteria get better conditions, and nitrogen fixation increases (Abdena, 2013). Liming not only improves the activity of rhizobia but also that of nitrifiers. Porosities and moisture holding capacity of the soils were positively significantly (p< 0.01) impacted by liming. On the contrary, bulk densities of the soils were negatively significantly affected by liming. This indicates that liming can also be used to improve soil structure (Getachew *et al*., 2017). The *C*:*N* ratio was not significantly affected by liming. This may be because the two components of SOM *i.e*,*C* and *N*, were proportionally affected by liming. Phosphorus availability of all the soils was positively significantly (P< 0.01) impacted by liming. This is because liming leads to substitution reaction of cations (Ca^{2+} and Mg^{2+}) in the liming materials with phosphorus fixing cations (Al^{3+} and Fe^{3+}) and converts phosphorus compounds into easily soluble ones.

Table 2. Selected physicochemical properties within the six sample soils before and after liming

Sample Site	*pH* (*H_2O*)	Bd (g cm^{-3})	Porosity (%)	MC (%)	CEC (CmolKg^{-1})	EC (μS cm^{-1})	EA (Cmol Kg^{-1})	SO*C* (%)	T*N* (%)	T*P* (mg Kg^{-1})	*C*:*N* (%)	Textural Class
	Physicochemical properties of the six sample soils before liming											
AA	4.72^{f}	1.45^{c}	37.22^{g}	21.12^{g}	28.14^{f}	32.43^{f}	2.45^{c}	0.89^{b}	0.06^{d}	1.67^{i}	14.83^{a}	Silty-Clay
BD	4.54^{g}	1.76^{a}	30.31^{h}	24.88^{e}	36.59^{b}	30.25^{g}	2.56^{b}	0.97^{a}	0.02^{e}	1.76^{h}	12.13^{d}	Clay
KB	4.46^{g}	1.47^{c}	40.94^{f}	28.23^{d}	27.24^{f}	28.41^{i}	2.98^{a}	0.99^{a}	0.09^{a}	1.87^{g}	11.00^{e}	Clay-loam
KG	5.21^{d}	1.66^{b}	47.16^{b}	30.21^{c}	34.71^{c}	37.34^{b}	2.14^{c}	0.86^{b}	0.07^{c}	1.93^{f}	12.29^{c}	Silty-Clay
NG	4.97^{e}	1.68^{b}	50.00^{a}	27.36^{d}	36.32^{b}	33.35^{e}	2.28^{b}	0.88^{b}	0.07^{c}	1.39^{k}	12.57^{b}	Silty-Clay
WG	5.14^{d}	1.48^{c}	39.80^{d}	30.62^{c}	29.37^{d}	35.31^{c}	2.12^{c}	0.98^{a}	0.08^{b}	1.54^{j}	12.25^{c}	Clay-loam
	Physicochemical properties of the six sample soils after liming											
AA	6.80^{b}	1.31^{e}	43.39^{c}	23.22^{f}	30.34^{e}	34.46^{d}	0.65^{f}	0.28^{d}	0.02^{g}	2.68^{d}	14.82^{a}	Silty-Clay
BD	6.46^{c}	1.40^{d}	37.21^{g}	25.28^{e}	37.19^{a}	34.55^{d}	0.26^{g}	0.47^{c}	0.08^{b}	6.79^{a}	12.11^{d}	Clay
KB	6.42^{c}	1.23^{d}	43.00^{c}	30.43^{c}	29.44^{f}	29.49^{h}	1.18^{d}	0.45^{c}	0.06^{d}	4.88^{b}	11.02^{e}	Clay-loam
KG	7.12^{a}	1.43^{d}	47.34^{b}	33.26^{b}	36.72^{b}	39.24^{a}	0.64^{f}	0.27^{d}	0.03^{f}	3.79^{c}	12.22^{c}	Silty-Clay
NG	6.88^{b}	1.43^{d}	51.28^{a}	30.38^{c}	37.38^{a}	35.35^{c}	0.98^{e}	0.26^{d}	0.03^{f}	1.34^{k}	12.52^{b}	Silty-Clay
WG	7.22^{a}	1.30^{e}	42.35^{e}	34.78^{a}	30.39^{d}	37.35^{b}	0.65^{f}	0.48^{c}	0.04^{e}	2.14^{e}	12.21^{c}	Clay-loam
CV	0.555	1.50	0.525	1.630	0.844	0.126	0.897	1.870	1.831	1.114	1.111	
R^2	0.976	0.998	0.996	0.969	0.998	0.977	0.996	0.988	0.988	0.999	0.979	
LSD	0.016	0.012	0.015	0.018	0.018	0.018	0.017	0.018	0.019	0.017	0.018	
F-*t*	**	**	**	**	**	**	**	**	**	**	ns	

Note: AA = AmumaAgalo sample site; BD = BikiltuDilla sample site; KB = KutallaBildimma sample site; KG = KoteGennasi sample site; NG = NasisiGenasi sample site; WG = Walitate Gida sample site; Bd = Bulk density; MC = Moisture content; CEC = Cataion exchange capacity; EC = Electrical conductivity; EA = Exchangeable acidity; O*C* = Organic carbon; T*N* = Total nitrogen; LR = Lime requirement; A*P* = Available phosphorus; CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.001$. Within a column, means with the same letters are not significantly different for each sample before and after liming.

3.3 Relationship among some soil physicochemical properties under lime treatments

The relationship (Pearson correlation matrix) among some soil physicochemical properties was analyzed as indicated in Table 3. Irrespective of the sample type, significant ($p< 0.01$) relationships were observed amongst the investigated soil physicochemical properties. As can be shown from the Pearson correlation matrix, CEC, EC, EA, SOM, T*N*, and A*P* have significant ($p< 0.01$) correlation amongst themselves and with some other soil physicochemical properties such as porosity, bulk density (Bd), and the *C*:*N* ratio. Available phosphorus had a significant ($p< 0.01$) positive correlation with all soil physicochemical properties except EA, with which it was significantly negatively correlated ($p< 0.01$). This is because when an exchangeable acidity increases, phosphorus becomes more and more fixed by aluminum and iron cations and becomes unavailable (Desalegn *et al.*, 2017). Except for *pH* and bulk density, SOM was significantly positively correlated with other soil properties. This is because as soil *pH* increases (acidity decreases), optimum soil conditions are created for the favors production of SOM by microorganisms (Adane, 2014).

Table 3. Pearson correlation (*r*) analysis for average soil physicochemical properties

	pH	Bd	Poro.	CEC	EC	EA	SOM	T*N*	*C*:*N*	A*P*
pH	1									
Bd	0.05	1								
Poro.	0.06	-0.87**	1							
CEC	0.53**	-0.32**	0.28*	1						
EC	-0.41**	0.18*	0.30*	0.33**	1					
EA	0.62**	0.30*	0.21*	-0.22*	-0.26*	1				
SOM	-0.67**	0.30*	0.45**	0.86**	0.42**	0.24*	1			
T*N*	-0.63**	0.26*	0.48**	0.68**	0.02	-0.32**	0.98**	1		
C:*N*	0.24*	0.18*	0.46**	0.57**	0.03	-0.16*	0.89**	0.65**	1	
A*P*	0.68**	0.14*	0.13*	0.48**	0.16*	-0.69**	0.66**	0.43**	0.38**	1

Bd= Bulk density; Poro= porosity; CEC= Cation exchange capacity; EC= Electric conductivity; EA= Exchangeable acidity; SOM= Soil organic matter; T*N*= Total nitrogen; *C*:*N*= Carbon to nitrogen ratio; A*P*= Available phosphorus. ** and * = Significant correlations at p= 0.01 and p= 0.05 respectively.

3.4 Nutrient bioavailability as affected by liming

Availabilities of macronutrients (Ca, K, and Mg) and the micronutrients (Zn, Fe, Cu, and Mn) were significantly ($p \leq 0.01$) affected liming, as shown in (Table 4). Potassium availability was increased significantly ($p \leq 0.01$) after liming and incubation of all of the soils. The initial status of available potassium ranged from 1.07 to 3.82 ppm, but after liming and incubation, it ranged from 4.05 to 5.68 ppm. This could be due to replacing potassium from the exchange sites by some cations, such as Ca^{2+} and Mg^{2+} from the liming materials, that increase its availability. After liming, the CEC of the soils was enhanced in soils with pH-dependent charges, and this improved the capacity of the soils to hold potassium. The available form of calcium showed increments ranging from 2.58 to 5.93 ppm before liming and ranged from 36.84 to 50.29 ppm. Liming the soil significantly increased the available form of calcium in the soil. This could be due to the application of Ca^{2+} from the liming materials and due to improvement in some soil physicochemical properties that determine calcium availability. The status of available Mg^{2+} ranged from 1.86 to 4.02 ppm before liming and ranged from 58.35 to 98.60 ppm after liming and incubating for 120 days. This indicates that liming brought a significant ($p \leq 0.01$) difference in Mg^{2+} availability. Similar to the case of Ca^{2+}, this could be due to the application of Mg^{2+}

from the liming materials and due to improvement in some soil physicochemical properties that determine Mg^{2+} availability (Opala *et al.*, 2018).

Regarding the effect of liming of availabilities of the micronutrients (Fe, Zn, Mn, Cu, and Mo), all of them showed a significant ($p \leq 0.01$) decrease after liming (Desalegn *et al.*, 2017). This can be attributed to the exchange of reduced ferrous iron and manganese ions from the exchange sites by the added Ca and Mg with liming materials and its subsequent precipitation. However, the effects of liming the soils were highly dependent on soil physicochemical properties (Adane, 2014).

On the other hand, the effect of liming on nutrient availability was affected by some soil physicochemical properties such as soil texture, pH, CEC, and SOC. As can be seen from Table 2 and Table 4, nutrient availabilities were significantly affected ($P<$ 0.01) by the soil physicochemical properties such as textures, pH, CEC, and SOC. The highest values of availabilities for most of the nutrients were observed in clay loam, loam, and silty-clay soil textural classes with pH values greater than 6.5 after liming the soils. This can be attributed to the fact that clay-rich soils contain relatively higher CEC, a property that determines the reaction of liming materials with inherent cations in the soil exchange sites. With soils having higher CEC, there is a relatively higher chance for the cations in liming materials to replace exchangeable acid cations, hence improving nutrient availabilities (Kebede *et al.*, 2017).

Table 4. Exchangeable cations in the six different soils before and after liming (ppm)

Sample Site	K^+	Ca^{2+}	Mg^{2+}	Fe^{3+}	Mn^{2+}	Zn^{2+}	Cu^+	Mo	Al^{3+} mgL^{-1}
Exchangeable cations in the six different soils before liming									
AA	1.21^g	7.42^f	2.44^j	901.01^e	112.64^e	4.75^c	3.59^h	17.92^e	510.42^f
BD	1.07^g	5.93^g	3.33^h	921.87^d	113.58^e	4.63^d	2.96^i	12.09^f	641.01^c
KB	1.16^g	2.58^j	1.86^k	1120.11^a	122.64^c	3.44^g	4.89^f	20.05^d	621.74^d
KG	2.59^f	3.77^i	2.48^i	992.65^c	137.61^a	3.76^e	5.18^e	26.79^c	531.97^e
NG	3.82^e	5.65^g	4.02^g	1102.25^b	125.51^b	6.92^a	7.92^a	32.98^b	764.15^a
WG	2.76^f	4.47^h	1.86^k	1121.06^a	118.57^d	6.87^b	7.12^b	33.24^a	745.83^b
Exchangeable cations in the six different soils after liming									
AA	4.39^c	36.84^e	66.08^d	34.29^j	27.65^g	2.14^i	5.28^e	1.76^j	27.61^k
BD	4.05^d	36.93^e	58.35^f	33.57^k	27.75^f	2.36^h	4.11^g	1.26^k	27.86^k
KB	4.74^b	39.38^d	59.82^e	47.99^f	25.51^h	3.78^e	6.92^c	3.93^g	37.91^j
KG	5.68^a	45.43^c	76.84^c	35.02^i	23.52^j	3.52^g	7.18^b	2.01^h	42.01^h
NG	4.77^b	50.29^a	98.6^a	46.85^g	27.78^f	2.42^h	7.79^a	1.86^i	48.06^g
WG	5.66^a	48.96^b	91.4^b	44.21^h	25.35^i	3.46^g	6.32^d	1.17^l	41.94^i
CV	2.30	0.399	0.331	1.634	1.072	0.854	1.674	1.172	0.454
R^2	0.998	0.996	0.996	0.998	0.999	0.995	0.998	0.999	0.995
LSD	0.015	0.015	0.014	0.017	0.013	0.026	0.016	0.015	0.048
F-t	**	**	**	**	**	**	**	**	**

Note: AA= AmumaAgalo sample site; BD= BikiltuDilla sample site; KB= KutallaBildimma sample site; KG= KoteGennasi sample site; NG= NasisiGenasi sample site; WG= WalitateGidda sample site; CV= Coefficient of variance; LSD= Least significant difference; ** = Significant at $p \leq 0.01$. Within a column, means with the same letters are not significantly different for each sample before and after liming.

4 Conclusion

This study assessed the impacts of applying proper liming materials to acid soils on plant nutrient bioavailability and soil physicochemical properties. The results revealed that nutrient availabilities can be enhanced by using appropriate liming materials and proper liming rates. In addition, soil physicochemical properties can be amended by liming. In all of the six acid soils studied, the effect of liming was significant to improve nutrient bioavailability. In addition, the liming of acid soils can reduce the contents of toxic elements such as *Al*, *Fe*, *Mn*, and improve crop healthy growth and production. Therefore, area-specific investigation of soil acidity status and liming conditions can be of great importance for agricultural production. Some soils may show nutrient deficiency while inherently having a high amount of important plant nutrients. This is due to the fixation of nutrients in acidic conditions. Therefore, we recommend considering using liming instead of applying more inorganic fertilizers to enhance nutrient availability and efficient use.

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Conflict of Interest

There is no conflict of interest to be disclosed.

Data Availability

Portion or all the data will be available up on formal request to the author.

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Determinants of food security among rural households in Majang Zone, Gambella Region, South-western Ethiopia

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Abstract

Attaining food security is a basic human right and a priority development agenda, although the challenge remains tough in the least developed countries. This study was conducted to evaluate the food security status of households and the factors influencing it in the Majang Zone. A multistage sampling method was utilized to select 320 households. The research adopted a mixed-methods approach, incorporating questionnaires, focus group discussions (FGDs), and key informant interviews (KIIs) to collect data. The analysis of the data was performed using descriptive statistics and binary logistic regression. The findings revealed that approximately 53% of the respondents were classified as food secure, while 47% were deemed food insecure. Significant positive determinants of household food security included beehives ($p<0.05$), formal education ($p<0.01$), landholding ($p<0.01$), oxen ploughing ($p<0.05$), livestock ownership ($p<0.05$), farm income ($p<0.01$), extension support ($p<0.01$), and family size ($p<0.10$). Conversely, age ($p<0.05$) and pesticide use ($p<0.05$) exhibited negative correlations. An increase of one unit in these factors would result in an enhancement of food security by 0.1014, 2.138, 1.489, 2.237, 0.9674, 0.0001, 2.469, and 0.7226 units, respectively. Similarly, a unit increase in the age of households and pesticide use tend to reduce food security status by 0.1091 and 2.071 units, respectively. The limitations of improved agricultural technologies such as improved inputs for crop and livestock; small irrigation schemes; institutions including credit services and cooperatives; and infrastructural developments, namely roads, niche markets, and rural electrification, coupled with undiversified income sources, call for holistic and sustainable strategic intervention from concerned bodies of the government and stakeholders at all levels to curb food insecurity challenges.

Keywords/Phrases: Food Consumption Score, Food security, Households, Logit, Majang

1 Introduction

Although it is still difficult, especially in low-income nations, ensuring food and nutritional security is a human and constitutional right of all residents. Food safety is maintained when "all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (Clay, 2002, p. 2). Over 250 million individuals in Africa are among the nearly 690 million people who have experienced hunger worldwide despite attempts to address food security challenges (FAO *et al*., 2021). By 2020, the COVID-19 pandemic may have impacted 83–132 million individuals globally. This is an added challenge to 25 million estimated people living at or below the threshold of survival, Ethiopia continues to have a very high rate of poverty and food insecurity (Diriba, 2020). According to estimates from FAO *et al*. (2021) and IPC (2020), 8.5 million of them experienced acute food insecurity in the beginning of 2020. Approximately 10.2 million individuals faced emergency food security situations, as reported by Luminița

(2016). Debebe (2018) indicates that around 52% of the rural population and 36% of the urban population consume less than the minimum recommended intake of 2100 kcal per person per day. Over eight million individuals benefit from PSNP transfers due to the government's inclination to widen the food gap through food assistance (Gilligan *et al*., 2023).

Food insecurity and unsustainable food systems in Ethiopia are primarily caused by natural, social, physical, economic, and political reasons (Endalew *et al*., 2015; World Bank, 2010; Regassa, 2011; FAO, 2010; Andersson *et al*., 2011; Eneyew and Bekele, 2012). Another issue, according to Keller (2009), is gaps in program and policy implementation. According to Simane *et al*. (2016), drought, flooding, ecosystems, and biodiversity degradation are among the main reasons. The primary causes of food insecurity in Ethiopia, according to the FAO (2017), were famine and unpredictable rainfall or seasonal differences. Throughout the nation's history, frequent floods and droughts—like the most recent El Niño devastation in 2015 and 2016—have resulted in significant losses of life and property (FAO *et al*., 2017; UNDP *et al*., 2010; World Bank, 2017). Over the past fifty years, there have been more than fifteen drought occurrences in Ethiopia (Kasie, 2017). Additionally, it has been asserted that the nation is structurally food insecure, with food availability being hindered by political, economic, and infrastructural unrest, even though food may eventually become available (Vedeld *et al*., 2007).

Food insecurity in the research area has been linked to several factors, such as the improper use of natural resources, drought conditions, inadequate off-farm employment opportunities, health issues, limited access to markets and credit, insufficient access to drinking water and sanitation, gaps in policy, and the rising prices of food products (Mathewos & Bewuketu, 2018; Guyalo *et al*., 2022; Girma & Muluneh, 2021). Few studies have been done to address the fundamental problems that lead to food insecurity, notwithstanding the difficulties in guaranteeing food security. Regular government documentation and emergency assessment reports provide the majority of the information currently accessible on food security. This mismatch has led to inconsistent planning and execution of food security measures, redundant efforts, and improper prioritization. Additionally, a large number of households in the region rely on the forest and non-timber items associated to it for their livelihoods; nevertheless, scientific studies rarely address these issues. In order to solve these problems, the Majang zone's rural households' food security status was examined in relation to food security determinants.

2 Materials and Methods

2.1 Description of the Study Area

The Majang zone in the Gambella Region of Ethiopia was the site of this investigation. The zone is situated between latitudes 7°4'2.41" N and 7°46'47.79" N and longitudes 34°36'30.54" E and 35°38'48.00" E. The entire research area is made up of the Zone's two districts, Godere and Mangeshi (Figure 1). The study location experienced hot and humid weather. The mean annual rainfall was calculated to be around 2100 mm, despite the lack of meteorological stations. The range of the mean temperature was 20 to 33°C. According to Guyalo *et al*. (2022), the region is distinguished by a flat to gently sloping terrain with deep, rocky valleys around major streams and hills. The population of the zone reaches 89,033, with 46,119 men and 42,914 women, according to the CSA's predicted population census for 2022. Its estimated population density was 39.5 persons per square kilometer. The two districts, Godere and Mangeshi, have projected populations of 61,079 and 27,954, respectively, with an average family size of 5.3 individuals. Additionally, a significant proportion of the population is under the age of 20, exceeding 60%. Approximately 88% of the inhabitants reside in rural regions.

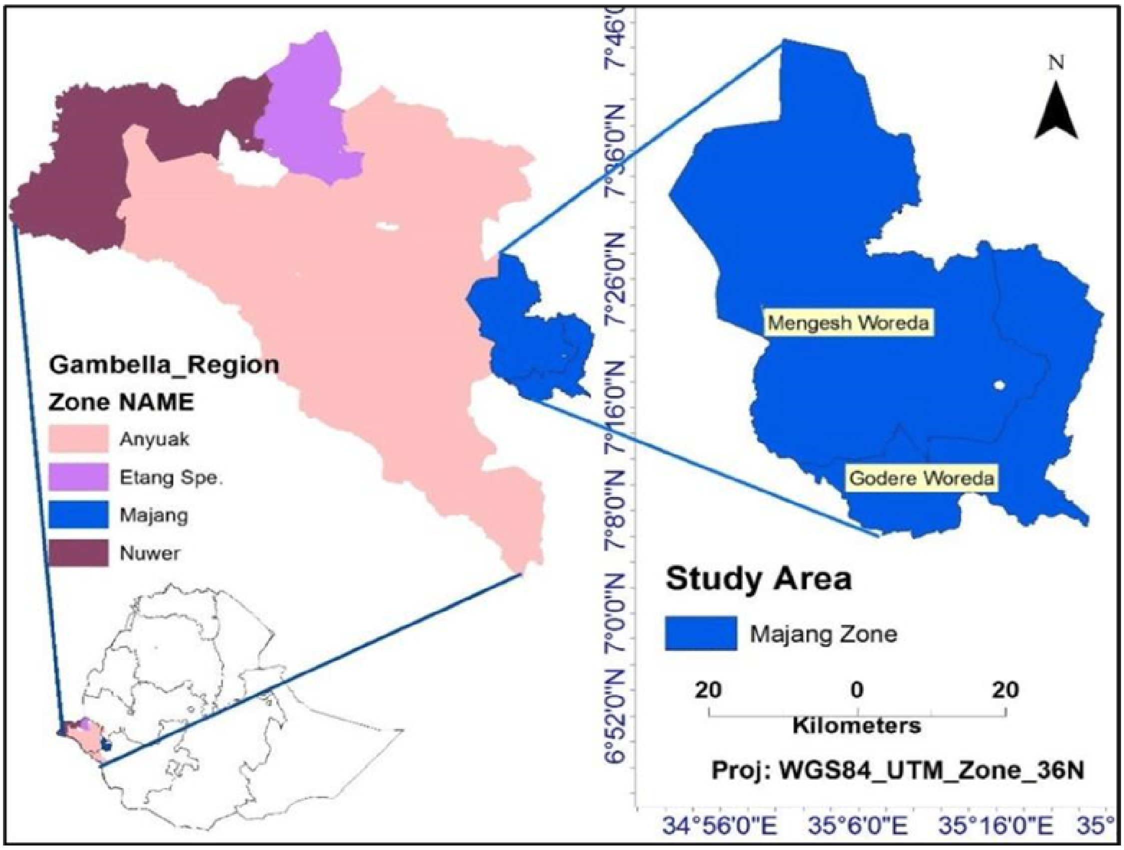

Figure 1. Map of the study area: Adapted from Mathewos & Bewuketu (2018)

2.2 Study Design and Data Collection Tools

The current research utilized an embedded design that sought to gather both qualitative and quantitative data either simultaneously or in sequence, while ensuring that the quantitative findings aligned with the qualitative findings (Creswell, 2009). Degefa (2006) recognized the mixed research design as the cornerstone of food security research, as it facilitates the examination of food security from various perspectives. This research employed household-based cross-sectional data. Consequently, both qualitative and quantitative approaches were implemented to collect data from primary and secondary sources. The methods employed for data collection included key informant interviews (KIIs), focus group discussions (FGDs), structured surveys, and desk reviews. To obtain information on food consumption, the WFP's standard survey module for the food consumption score (FCS) was utilized (WFP, 2008).

Primary data were collected using structured household survey questionnaires, FGDs, and KIIs from household respondents, rural extension workers, government and non-governmental organization (NGO) experts, and officials working on food security. Supplementary sources from published articles, periodic reports, and assessment were used to augment the secondary data requirement. Ten FGD sessions were held in each village, using the developed terms of reference administered to a group of 7-10 individuals. Both in-depth interviews and FGDs were conducted to triangulate the reliability and validity of the information gathered using other means.

2.3 Sample Size Determination

A multistage sampling procedure was implemented to select the households for the study. Initially, two districts, Mangeshi and Godere, were intentionally chosen since the zone comprises only these two districts, which share similar livelihoods and administrative boundaries. Subsequently, a systematic random sampling method was employed to select 10 villages—four from Godere and six from Mangeshi—out of a total of 32 villages, based on the premise that a substantial sampling ratio (approximately 30%) was suitable for small populations (less than 1,000). The selected villages were determined based on prior discussions and assumptions regarding subsistence agriculture, the predominance of the Majang community, and their reliance on forest-based livelihoods. To ascertain the sample size for each village, the projected population (households) for 2022 was utilized to calculate the number of respondent households from each village, in accordance with the total household proportion share. The overall population and number of households in the 10 villages are estimated to be 15,826 and 3,557, respectively. Lastly, household respondents were randomly selected by employing the probability proportional to size technique for larger populations, as outlined by Cochran (1977).

$$n_0 = \frac{Z^2 pq}{e^2} \tag{1}$$

where, n_0 is the sample size and Z^2 is the abscissa of the normal curve that cuts off an area α at the tails ($1-\alpha$ equals the desired confidence level).

For this study, a 95% confidence interval was utilized, with the Z table value set at 1.96; e signifies the required level of precision; p (0.6) indicates the estimated proportion of an attribute or the total number of food-insecure households within the zone's population; and q is defined as 1-p, as noted in the reports of DRMFSS (2015).

According to the aforementioned formula, the sample size was calculated to be 369 households. Considering (Cochran, 1977) the sample size adjustment for instances where sample sizes exceed 5% of the population, the final sample size is established as follows:

$$n_1 = \frac{n_0}{1+\frac{n_0}{N}} \tag{2}$$

where, n_0 = the required return sample size, n_1 = the final sample size because the sample > 5% of the population and N = the population size.

Consequently, the final sample size was calculated as [369/1+ (369/3557)] =334. Due to the lack of complete information in certain household data, a few were excluded, resulting in 320 sample households forming the sampling unit for the final analysis.

2.4 Data Analysis

STATA version 13 was used to investigate the quantitative data on the variables influencing food security using both descriptive and bivariate econometric analytic techniques. To support and enhance the findings of the quantitative study, information from the responses was extracted, grouped, and synthesized to assess qualitative data.

Data was gathered using the Food Consumption Score (FCS) standard module in accordance with WFP (2008) criteria. The mean, frequency, standard deviation, and percentage constituted the descriptive statistics employed to evaluate the extent of influence of all the factors that affect household food security.

The correlates of household food security were examined using logistic regression (binary logit). The variables being studied and several related research articles, such as those by Moroda *et al.* (2018) and Hailu *et al.* (2018), were used to specify the binary logit econometric model. Unless the logit model is comparatively simpler mathematically, there is no strong argument for selecting it over the probit model.

The following mathematical presentation specifies the logit model's functional form:

Logit model:
$ln(\frac{p}{(1-p)}) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n + \varepsilon$

where, p is the probability of being food secure; β_0 is the intercept; $\beta_1, \beta_2, ..., \beta_0$ are the coefficients of the explanatory variables $X_1, X_2, ..., X_1$; and ε is the error term.

$$P_i = E(Y = \frac{1}{X_i} = \frac{1}{1+e^{-(\beta_0+\beta_j X_i)}}) \tag{3}$$

Substituting $(\beta_0 + \beta_j X_i)$ by Z_i, equation 3 becomes:

$$P_i = \frac{1}{1+e^{Z_i}} = \frac{e^{Z_i}}{1+e^{Z_i}} \tag{4}$$

where $P_i = E(Y = 1)$ is the probability that a household is food-secure. Z_i is a set of explanatory variables for the i^{th} household and β_0 and β_j are the parameters to be estimated.

If P_i indicates the probability of a household being food secure, as outlined in equation 2, then the probability of food insecurity can be articulated as follows:

$$1 - P_i = \frac{1}{1 + e^{Z_i}} \quad (5)$$

The odds ratio is calculated with equation 6:

$$L_i = ln(\frac{P_i}{1 - P_i}) = \frac{e^{Z_i}/1 + e^{Z_i}}{1/1 + e^{Z_i}} = e^{Z_i} \quad (6)$$

Hence, the logit model used to predict the odds of household food security is given by question 7.

$$L_i = ln(\frac{P_i}{1 - P_i}) = Z_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + u_i \quad (7)$$

Where, the coefficients of the variables to be estimated are denoted by β_i, where i = 1, 2, … j, and β_0 is a constant. A vector of the explanatory variables is called X_i.

The Food Consumption Score (FCS) is derived from the variety of foods and the frequency of their consumption over a week-long period. The FCS is represented on a continuous scale, which is then used to classify households into established thresholds. Consequently, standard statistical measures, including the mean and variance, can be computed, allowing for the analysis of mean trends over time and across different categories. Additionally, frequencies and cross-tabulations can be established for the various food consumption groups.

In terms of methodology, the food items were categorized into eight standard food groups, with a maximum consumption frequency of 7 days per week. Following this, the frequency of consumption for each food group was multiplied by a designated weight, reflecting its nutritional value. These resulting figures were then aggregated to calculate the FCS.

The typical thresholds used by WFP (2008) are 0-21 (poor), 21.5-35 (borderline), and >35 (acceptable). Nevertheless, for populations with a significant frequency of oil and sugar intake (daily or nearly daily), alternative cut-off points are suggested as follows: 0-28 (poor), 28.5-42 (borderline), and greater than 42 (acceptable) (Tesafa *et al.*, 2022; WFP, 2010). Because oil and sugar are consumed daily by people in almost all parts of Sub-Saharan Africa, including Ethiopia, the latter cut-off categories were used to set the FCS categories of the sampled households (WFP, 2008).

$$FCS_h = \sum_{i=1}^{n} w_i D_i \quad (8)$$

where FCS_h is the food consumption score of household h, w_i is the weight of food group i, and D_i is the number of days of consumption in the last seven days.

2.5 Definition and measurement of the study variables

Dependent variable

The household food balance sheet, along with another method for assessing food consumption (measured in kilocalories/day/AE), is widely acknowledged as the primary approach utilized in most studies to evaluate food security (Feleke *et al.*, 2013). Furthermore, as stated by the WFP (2008), the Food Consumption Score (FCS), which assesses both caloric intake and the quality of the diet at the household level, is a recognized technique for determining food security. Consequently, the food security status of households is ascertained through the FCS. To classify families into three distinct food consumption categories, the household food consumption score is analyzed against established cut-off points:

0-28: Poor
28.1-42: Borderline
42: Acceptable

These groups reflect the food consumption status of the surveyed households. When determining the threshold cut-off value for food security, the assumptions of the WFP (2010) and Tesafa *et al.* (2022) were considered. As the value of the FCS falls between 0 and 112, one finds an FCS with a zero value, and an FCS of 112 is the maximum score (which means that all food groups were consumed by all seven days by household members).

Furthermore, by establishing 42 as the threshold for the Food Consumption Score (FCS), households were categorized into food secure and food insecure groups to evaluate the risk factors associated with food insecurity. Consequently, any household with an FCS of 42 or below was classified as food insecure, while those with an FCS of 42 or above were considered food secure. Thus, when food security is confirmed, the dependent variable, which indicates food security status, is assigned a value of 1 (greater than 42), and if it is not confirmed, it receives a value of 0 (less than or equal to 42). A satisfactory percentage indicates food security, whereas the proportion of the population experiencing low and borderline food security reflects the prevalence of food insecurity (WFP, 2010).

Independent variables

Age of household head (AGE)**:** A continuous variable quantified in years. It is anticipated that younger households will exhibit superior food security.

Sex (SEXH)**:** This is a binary variable posited on the assumption that male-headed households have a higher likelihood of achieving food security.

Family size of households (FSZH)**:** Family size denotes the total count of individuals within a household. This is a continuous variable. It is hypothesized that larger families, due to having members of productive age, engage in a variety of productive endeavors both on farms and in off-farm activities to aid in achieving food security.

Marital status of household (MSTH)**:** This is a categorical variable that categorizes households as married, unmarried, divorced, and widowed. Married people are assumed to be better able to fulfil their food needs than single people.

Dependency ratio (DEPR)**:** This variable is measured on a ratio scale by dividing the total household size by the number of individuals working. High dependency ratio indicates less probability of being food secured (Fekadu & Mequanent, 2010; Feleke *et al.*, 2003).

Educational Status of Household (EDHH)**:** Educated members of a household were hypothesized to remain food secure. The variable was measured on a dummy scale, denoted as 1 if the household had attended formal schooling and 0 if not.

Income diversity (INCD)**:** This variable is expressed in categorical scales, based on the sources of income available to households. The availability of diverse incomes to a household secures the purchasing power of food and other necessities. This aspect is strongly related to food security.

Landholding Size (LHSH)**:** Landholding size is measured in hectares. Households with large amounts of fertile cultivated land are expected to have a greater probability becoming food secure.

Livestock assets (Tropical livestock unit, TLU)**:** The size and type of livestock owned assumed to increase food security.

Oxen ploughing of farmland (OXPL)**:** The practice enables to retain the advantages of time, labor, and energy. Hypothetically, it has a positive correlation with household food security.

Agricultural extension service (AEXS)**:** Technical visit by experts assumed to increase the chance of being food secure.

Improved seed use (IMPS)**:** dummy variable. Farmers who utilize improved seeds have a greater probability of securing food than those who are unable to use improved seeds.

Fertilizer use (FRTU)**:** It was measured on a dummy scale with values of 1 and 0 for yes and no answers, respectively.

Pesticides/Fungicide Use (PEST)**:** It is expected to increase the probability of food security. This was measured using a dummy scale.

Veterinary service (VETS)**:** A dummy variable denoted 1 for yes and 0 otherwise, where service provision supports attaining food security.

Irrigation use (IRRU)**:** A dummy variable that takes the value of 1 if irrigation is used to produce a crop and 0 otherwise. Irrigation reduces the dependency of farmers on rain and enables the efficient utilization of resources such as water, time, land, and labor to increase production.

Farmers' Training Center (FTC)**:** It is hypothesized that an institution will make a positive contribution to food security. The variable is a dummy variable that is measured as 1 for yes or 0 for no.

Beehives possessed (BEHV)**:** A variable expressed on a ratio scale based on the number of beehives owned. Households with a greater number of beehives are expected to become more food-secure.

Access to Credit Service (ACSV)**:** It is a dummy variable that has a value of zero if the household does not accept credit and one if they do. Therefore, the likelihood of food security is higher for a household that has access to finance.

Cooperative Membership (COOP)**:** This is a dummy variable that positively correlated with food security.

Off-farm income (OFINC)**:** Income is measured in terms of birr and is therefore a continuous variable. Off-farm income is positively associated with household food security.

On-farm income (FAINC)**:** It is measured in a manner similar to that for off-farm income. The a priori assumptions about food security were positive.

3 Results and Discussions

3.1 Socioeconomic characteristics of respondents

Tables 1, Figure 2, and Figure 3 present the households' social and economic characteristics. The research involved 320 rural households, the majority of which (90%) relied on agriculture as their major occupation to fulfill their livelihood. Approximately 79% of them were married, and 88% were male-headed households, indicating the dominance of male households in the farming community.

The average age of the households involved in the study was around 40 years, with the youngest participant being 18 years old and the oldest participant being 75 years old, respectively. On average, a household is composed of five family members, with a family size on par with the national average. Moreover, the mean landholding size (2.63 ha) of households in the study area was threefold higher than the Ethiopian CSA (Regassa *et al.*, 2013) national (0.84 ha) and regional (0.63 ha) averages.

The mean annual farm and off-farm incomes of the households were calculated to be 20,273 birr and 495 birr, respectively; the mean per capita per annum was 4,054 and 100, respectively, for on-farm and off-farm incomes.

A multitude of factors contributed to the elevated levels of food insecurity observed in the research area, as indicated by the overall descriptive statistics. According to the food consumption indicators, the findings revealed that 53.12% of households were classified as food secure, while 46.88% were deemed food insecure. The average percentage of dependent members within households was higher (108%) in the study area, with the maximum percentage soaring to 250%.

Table 1. Descriptive statistics of the variables on the ratio scale

Variable	Obs	Mean	Std. Dev.	Min	Max
Age of the Household Head	320	40.36	11.33123	18	75
Family Size of the Household	320	4.99	1.80208	1	10
Dependency Ratio (%)	320	108.65	63.48359	0	250
Food Consumption Score	320	44.34	15.43502	9	108
Landholding Size	320	2.63	2.163528	0	13
Tropical Livestock Unit	320	.59	.9519454	0	4.2
Beehives possessed	320	5.00	10.45847	0	50
Off-farm income	320	495	1590.34	0	8000
On-farm income	320	20273.38	14810.23	0	49650

Source: Own survey data

3.2 The food security status of respondents

The results of the descriptive analysis further clarified that among the total households surveyed, around 88% were married, 8% were single, 2% were divorced, and 2% were widowed regarding their marital status. Regarding their occupations, 89.7% of the household respondents depended solely on agriculture, the remaining 9.7% on agriculture and trade, and 0.6% on other forms of income activities.

In addition, 57.81% had not attended formal education, and 42.19% had attended elementary education (Figure 2). Almost three-fourths of the respondents claimed the absence of services and technologies that support agriculture.

Accordingly, approximately 60.94% of them did not receive agricultural extension service contact, although FTCs were constructed in their villages (60.62%), were not provided with improved seeds (74.38%), not supplementing their crop production using traditional irrigation schemes (87.19%), not involved in cooperative activities (83.13%), inaccessible to veterinary services (80%), unable to prepare and apply fertilizers (86.56%), cannot plough (66.25%) with oxen, unable to access credit services (82.19%), and in short of purchasing and applying chemical pesticides (67.50%).

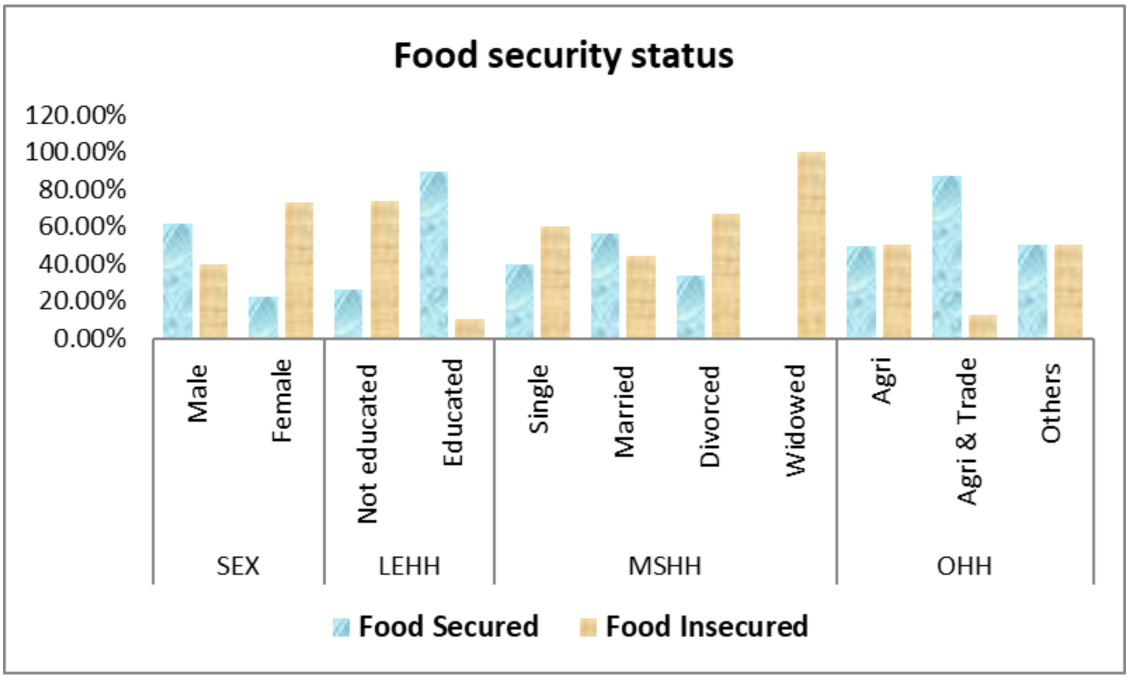

Figure 2. Descriptive statistics on the food security status of respondents
NB: LEHH-Level of Education, MSHH-Marital Status, and OHH-Occupation of Household Head.

The cross-tabulation results showed that among food-secure households, 91.18%, 92.94%, and 71.18% were male-headed, married, and had formal education, respectively. Within-group comparison ratios indicated that male-headed households (61.26%), married households (56.03%), and those who had attended formal education (89.63%) were more food secure. However, 22.39% of the females were headed, 31.58% were not married (single, widowed, or divorced), and 26.49% of those with no formal education were food secure.

Moreover, households with more than one occupation, agriculture, or trade (87.10%) had a greater chance of becoming food secure than those with only agriculture (49.48%) (Figure 3). Approximately 23.65% of the respondents participated and used inputs. A total of 125 households agreed to participate in extension services; 96% claimed food security, as did those who used improved seeds (87.80%), veterinary services (88.89%), organic fertilizers and access credit services (95.35%), pesticides (92.31%), cooperatives (95.52%), traditional irrigation (100%), and plowing with oxen (89.81%) (Figure 3).

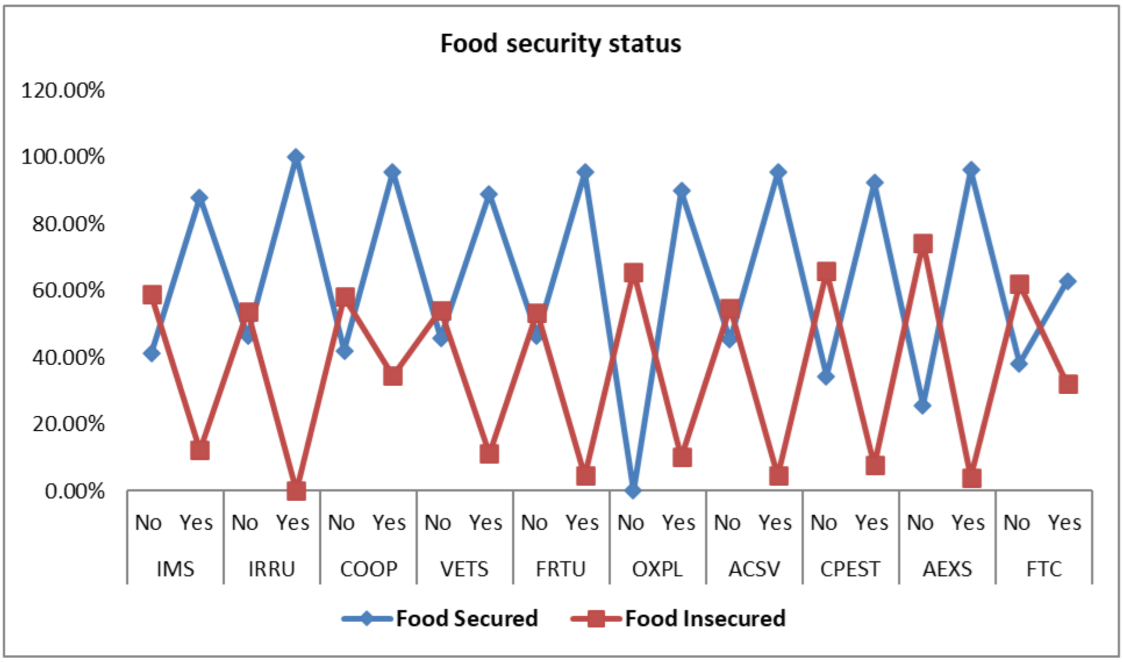

Figure 3. Food security statuses of the households as determined by dummy variables

NB: IMS-improved seed, IIRU-irrigation use, COOP-cooperative membership, VETS-access to veternary service, FRTU-fertiizer use, OXPL-oxen ploughing, ACSV-access to credit service, CPEST-pesticide use, AEXS-access to agricultural extension service and FTC-farmers' training center.

3.3 Econometric results of food security determinants

The food security status of households was evaluated based on the food consumption score categories established by the WFP in 2008. Ten of the 22 explanatory variables that were fitted to the designated model at different probability and influence levels demonstrated statistical significance.

The overall fitness of the model was checked using post-estimation tests (linktest, estat gof, estat classification, lsens, lroc). The link test is significant at _hat (p<0.01) and insignificant at _hatsq (p<0.374), indicating a perfect link between variables with no requirement of transformation. The chi-square test is also significant at 1% probability (pro > χ^2 = 0.0001). The goodness-of-fit test predicted the number of correctly predicted food-secure (95.88%) and insecure (96.67%) groups with prediction-based correctly classified values (96.25%) (Table 2).

The study used a logit model and Pearson's correlation analysis to evaluate food security status. Results showed that farm income, number of traditional beehives, formal education, agricultural land size, oxen plowing, livestock herds, access to extension support, and working family members have positive association with food security increment. However, the age and use of pesticides had significant negative predictive effects on food security status.

Table 2. The maximum likelihood estimates of the logistic regression model

Variables	Coef.	Robust Std. Err.	P value
Age of household head	-.1091**	.0483	0.024
Sex of household head	-.5101	.9599	0.595
Family size	.6119*	.3353	0.068
Marital status of household head	.9311	.8595	0.279
Dependency ratio	-.0092	.0075	0.219
Education level of household head	2.138***	.8174	0.009
Occupation of household head	-2.743	2.347	0.242
Land holding size	1.489***	.4764	0.002
Livestock ownership (TLU)	.9674**	.4936	0.050
Oxen ploughing	2.237**	1.023	0.029
Veterinary services	-1.061	1.192	0.373
Crop pesticides/fungicide	-2.071**	1.001	0.038
Farmers training center	-.5206	.6693	0.437
Agricultural extension service	2.469***	.9159	0.007
Fertilizer use	.7226	1.310	0.581
Improved seeds use	-.2208	.6414	0.731
Beehive owned	.1014**	.0459	0.027
Access to credit service	-1.613	1.518	0.288
Cooperative membership	1.872	1.333	0.160
Off-farm income	.0006	.0006	0.329
On-farm income	.0001***	.00003	0.003
_cons	-3.682	3.858	0.340
Number of obs = 320		Log likelihood = -35.181077	
Sensitivity (Food secured) =95.88%		Pseudo R^2 = 0.8409	
Specificity (Food insecured)=96.67%		LR $\chi^2(2)$ = 372.00	
Correctly classified=96.25%		Prob > χ^2 = 0.0000	

Source: Own survey data

NB:***, **, and * denote very highly significant, highly significant and significant*

The findings presented in Table 2 demonstrate that the age of a household is inversely associated with food security. The negative coefficient signifies a statistically significant relationship (p<0.5) that is negative in nature between the age of the household and its food security status. With other factors held constant, the results showed that households became 0.1091 times less food secure as they got older (one additional year to live). The result is in agreement the work of Mohammed *et al.* (2021), Sani & Kemaw (2019b), and Hailu *et al.* (2018). These groups of people support their assertion that older households increase the dependency ratio in the household, and since household heads are younger, they are more likely to be physically strong and aspire to participate in diverse income-generating activities. In contrast to this research, Awoke *et al.* (2022) reported that age has a positive relationship with food security, given that the experience gained and wealth accumulated over time enables households to be more food secure.

The correlation between family size and food security is rarely positive in studies concerning food security. Nevertheless, the findings of this study indicate a positive and statistically significant association at the 10% probability level. Consequently, an increase of one unit in the number of families enhances the food security status of households by 0.6119 units, assuming other variables remain constant. This can be explained by the fact that households with larger family sizes, particularly when they consist of active adults, can contribute more labor to agricultural tasks, thereby boosting production and productivity. Consistent with this, the research conducted by Alemu (2013) demonstrated that a greater number of family members facilitates increased labor for production and positively correlates with the food security status of households.

Education is among the priority factors, as it contributes to the majority of the participants' efforts to improve their attainment of food security. Educated households tend to have more capacity to work efficiently by receiving and adopting improved technologies, participating in diversified income-generating activities, planning their working activities, keeping records of important events, and having knowledge of food and nutrition to smoothen their food basket requirements. As previously hypothesized, education has significance at the 1% probability level, with a coefficient portraying an almost 2.14 unit folds greater chance of being food secure than people who did not attend school. There was also a strong positive correlation (0.63) between these two factors. In support of our findings, Dagne (2016), Olayemi, (2012), and Mbukwa (2013) justified the necessity of formal education to enhance households' food security status.

The availability and size of agricultural land are the most basic asset endowments for agriculture-based rural livelihoods. In the Majang zone, land ownership is crucial for households, not only for agricultural activities, but also for providing forest-covered land for traditional beehives, a major component of their income source. Nearly 92% of the sampled households verified that agriculture was their primary mainstay. The results showed statistical significance at the 1% probability level (Table 2). Interpretively, possessing one more hectare of agricultural land increases the probability of becoming more (1.489 units) food secure. The correlation analysis results confirmed the existence of a positive and strong (72.41%) correlation between food security status and landholding size. Numerous studies (Tesafa *et al*., 2022; Agidew & Singh, 2017; Ahmed *et al*., 2018; Mequanent & Esubalew, 2015) conducted in rural contexts inseparably support the results of this research.

Livestock production plays an integral role in rural households' lives. Even though the average TLU of the studied households remained at a few units (0.59), the results showed a significant contribution of livestock ownership to food security. The findings indicate that food security increased by 2.631 units if the household owned one additional livestock while keeping other factors constant, which is significant at a 5% probability. A study in the Gambella region of the Lare district by Boum (2013) reported similar findings in which households with a unit higher TLU were found to be 0.863 units more food-secure. Other studies have confirmed the existence of a positive association between livestock size in TLU and food security (Mohammed & Mohammed, 2021; Misgina, 2014; Siraje & Bekele, 2013).

The findings indicated that only a limited number of households within the study area possessed both access to and proficiency in utilizing oxen for plowing; those who did experienced the most significant advantages. According to this hypothesis, farmers employing oxen for plowing their fields have a 0.9674 unit greater likelihood of achieving food security compared to those who do not. Furthermore, it is anticipated that farm revenue will have a highly significant ($p<0.003$) effect on the food security status in the research area, as it is thought to positively influence household food security. Consequently, for each unit increase in agricultural revenue, the food security status of households is expected to improve by a factor of 1.0001. The results from Pearson's correlation analysis revealed a strong and positive relationship (81.10%) between farm revenue and household food security status. The conclusions drawn by Awoke *et al*. (2022), Dagne (2016), Hussein & Janekarnkij (2013), and Etxegarai-Legarreta and Sanchez-Famoso (2022), who documented a positive and significant effect of on-farm income on the food security of rural households across various regions of Ethiopia, align with the findings of this study.

The majority of food security research conducted in Ethiopia has paid insufficient attention to factors associated with apiary activities overall, and no studies have been specifically carried out in the research area. Beekeeping is often complementary to agriculture, providing additional income opportunities for its practitioners (Hussein & Janekarnkij, 2013). Apart from generating income and serving as direct food, the existence of apiary farms in or around crop farms is expected to increase crop productivity because of the pollination role of bees. Research in Kenya (Etxegarai-Legarreta & Sanchez-Famoso, 2022) has shown that apiculture has a relatively higher and more reliable monthly income than animal and crop production. The number of traditional beehives possessed is believed to determine the income and wealth ranking in the Majang community. The traditional forest honey production type (Mutua, 2018) is the dominant and main source of income for indigenous Majang households because the yield and quality of honey are compromised by forest tree species and their abundance (Araya, 2020). As initially proposed, maintaining the other variables at their zero mean and unit standard deviation, the quantity of beehives owned had a positive and statistically significant impact on household food security status at the 5% probability level. An increased likelihood of owning more beehives enhances food security by 0.1014 units. Empirical findings from a study conducted in southern Ethiopia by Tarekegn & Ayele (2020) support the notion that a 1% increase in the number of beehives is expected to boost honey production by 10.14%, thereby raising the chances of achieving food security. Similar results from Uganda revealed an increase in honey production with an increasing number of hives kept and colonized per farmer (Mubarik & Buyinza, 2020).

Receiving agricultural extension services has vitality comparable to, if not greater than, that of attending formal schooling in terms of ameliorating the food security needs of agriculture-based households. The extension service is a package of improved technologies for the agricultural sector intended to facilitate the transfer of best agricultural practices and technologies to enhance the production and productivity of farming households.

The findings from the logit model suggest that involvement in agricultural extension programs is expected to raise the probability of achieving food security by 0.3435 units when compared to those who do not participate, which is statistically significant at the 1% level, assuming all other factors remain constant. In a similar vein, Awoke *et al.* (2022) and Sani and Kemaw (2019b) determined that providing technical assistance to farmers is crucial for improving the food security status of smallholder farmers. It was projected that resources such as fertilizers, pesticides, artificial insemination, and enhanced seed varieties would significantly contribute to the increase in agricultural production output.

The study examined the impact of improved seeds, fertilizers, and chemical pesticides on food security in households. It found that pesticide use was statistically significant, but not for chemical fertilizers or artificial insemination technologies. The results showed that a unit increase in chemical pesticide use increased food insecurity by 12.6%, contradicting the prior hypothesis. The study suggests that misconceptions about fertilizers and the inaccessibility and unaffordability of these technologies may have contributed to low adoption and reduced agricultural commodity yields.

4 Conclusion

This research aimed to determine the factors influencing and assess the food security status of rural households within the study area. It intended to investigate the elements that affect food security in the region. Furthermore, the outcomes of this study align with similar research conducted in Ethiopia and globally. The results revealed that 53% of the households were food secure, while 47% were food insecure. Although the use of pesticides and the age of the households had a negative impact on food security status, factors such as beehives, formal education, landholding, oxen plowing, livestock ownership, farm income, extension support, and family size made a significant and positive contribution to food security.

It was also claimed limited participation in extension services (39.06%), FTC (Farmer Training Center) coverage (39.38%), use of improved seeds (25.62%), irrigation (12.81%), participation in cooperatives (20%), access to veterinary services (16.87%), organic fertilizer use (13.44%), plowing with oxen (33.75%), and access to credit services (17.81%). Similarly, the small average tropical livestock unit

(0.59) suggests that contribution of the livestock sector to food and nutrition has received less attention. The authors also noted a complete absence of chemical fertilizer use in the study area.

Recommendations

Coordinated effort among national, regional, and local adminstrations and offices, such as those responsible for agriculture, climate and environment, forestry, disaster risk reduction and management, credit provision, education, and health, aligned with local development projects engaging in similar activities, must prioritize and implement effective food security policies and strategies in the study area. These should include small-scale irrigation schemes, production-enhancing technologies like certified seeds and modern beehives, land certification for better land use, and ensuring the welfare of households relying on forest resources. Local, development-centered plans are crucial for long-term success, as even non-significant variables can be important for food security fulfillment.

Equally crucial, traditional apiary activities, being the major income-generating non-timber forest product for most of the Majang community, require technical support to increase the honey collected per hive, improve product quality, and enhance the frequency of harvest. This should be coupled with the introduction and use of modern beehives. We recommend, as a priority and important research agenda, that comparative research be undertaken to determine the food security conditions of the Majang community and the so-called highlanders, as they may have distinctive livelihoods and require targeted intervention measures accordingly. Additionally, research that measures the resilience of households to food insecurity is recommended, as it provides a new perspective on how to effectively plan for and analyze the effects of shocks and stressors threatening the well-being of households or communities through a long-term development strategy.

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Institutional arrangements and stakeholder knowledge of watershed management for food security improvement: a case study of Qersa District, East Haraghe Zone, Ethiopia

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Abstract
The importance of community-based watershed management for rural development is well acknowledged, yet its comprehensive nature remains underappreciated. This study examines the perceptions of stakeholders and their level of coordination in implementing the watershed approach and its impact on food security. Data was collected from 63 professionals with diverse roles across organizations and 337 farmers from three micro watersheds in Qarsa Woreda, East Hararghe Zone, using surveys and interviews. Results showed varying views: 36% of professionals and 12.6% of farmers see it as a holistic rural development strategy, while 9% of professionals and 36.5% of farmers view it mainly as soil and water conservation. Chi-square tests revealed significant differences in professional perspectives based on organizational role and experience (p-values of 0.05 and 0.01), but farmers' views were consistent across watersheds. The study also highlighted a lack of effective collaboration among stakeholders, both vertically and horizontally, in supporting local watershed management initiatives. To maximize the benefits of watershed management for food security, it is crucial to improve stakeholder understanding, enhance institutional coordination, and strengthen accountability mechanisms. Addressing these areas through better educational programs and collaborative efforts can support sustainable rural development and improve food security for communities and ecosystems.

Keywords/Phrases: Coordination, Farmers, Institutional Arrangement, Integration, Professionals, Rural Development

1 Introduction

Integrated Watershed Management (IWM) has gained global recognition as a critical strategy for fostering sustainable food security and mitigating environmental impacts. It is widely acknowledged for its ability to address complex environmental issues while promoting socio-economic resilience (Godfray *et al*., 2010; Munang *et al*., 2011; Gulati *et al*., 2012; FAO, 2021). Successful implementations in countries such as China, Sri Lanka, and the Philippines showcase IWM's effectiveness in managing environmental challenges, enhancing social equity, and improving economic stability (Suhas *et al*., 2010; Rawat, 2014; Parvathi, 2013). In sub-Saharan Africa, including Uganda and Kenya, IWM has also demonstrated success in ecological preservation, promoting sustainable land use practices, and increasing resilience to climate change impacts (Nick & Woldehanna, 2012; FAO, 2017).

In Ethiopia, watershed management was initially introduced in the 1970s to address soil erosion and land degradation through a top-down, centralized approach (Alemu & Kidane, 2014; Moken *et al*., 2015; Gadisa, 2016). This period was marked by "planning in the dark" due to unclear criteria for land rehabilitation technologies, coupled with a policy framework emphasizing stringent government regulation (Bantider *et al*., 2019). This approach often led to ineffective planning and persistent natural resource depletion (Hassen, 2022; UNEP, 2016;

Nigussie *et al.*, 2018), highlighting the limitations of the early integrated watershed management strategy (Mekonnen *et al.*, 2011; Tefera, 2015).

Since 1991, Ethiopia has made significant strides in watershed management by broadening its focus beyond soil and water conservation to include socio-economic and environmental objectives (German *et al.*, 2007; Bantider *et al.*, 2020). The introduction of various policies and strategies, such as the agricultural-led industrialization development policy, has integrated watershed management into broader economic and rural development goals, including food security (Assefa, 2012; Amogne, 2014; Bantider *et al.*, 2020). Additionally, the establishment of community-based participatory watershed management guidelines in 2005 has facilitated standardized planning and coordination among institutions (Desta *et al.*, 2005). Furthermore, the 2011 Climate-Resilient Green Economy (CRGE) initiative was developed to enhance sustainable watershed management and resilience to climate change impacts (FDRE, 2012). Despite some improvements in natural resource conservation, agricultural practices, and livelihoods, and fostering synergies among technologies, policies, and institutions, the watershed approach has not fully met expectations for advancing rural development and food security (Worku *et al.*, 2018; Mekuriaw, 2017; Gebregziabher *et al.*, 2016; Gashaw, 2015; Bantider *et al.*, 2019; Gashaw *et al.*, 2014; Alemu & Kidane, 2014).

One of the primary challenges in watershed management is the varied interpretation and understanding of its concept, which has led to confusion in conservation and development planning (Vasant & Lin, 2012; Beley & Bewket, 2015; Devi, 2015; FAO, 2017; Setyo, 2019; Elfithri *et al.*, 2018; Heal, 2019). This lack of consensus among stakeholders - who often possess differing knowledge, values, and priorities - results in fragmented approaches and conflicting objectives that undermine effective implementation (German *et al.*, 2007; Gashaw *et al.*, 2014; Alemu & Kidane, 2014; Tefera, 2015). Additionally, the absence of a cohesive institutional framework and inadequate knowledge exchange exacerbate these issues, leading to compromised outcomes (Reddy *et al.*, 2017; Arfasa & Tona, 2019; Thiemann *et al.*, 2018). Policies developed since 1990 have generally fallen short of their goals due to the limited scope of individual institutions and insufficient integration of local knowledge (Bantider *et al.*, 2020).

It is widely acknowledged that effective watershed management requires strong institutional frameworks and a shared understanding among stakeholders (Gulati *et al.*, 2012; Bantider, 2019; Katusiime, 2023). However, existing studies tend to focus on the physical aspects of watershed management and overlook the importance of institutional factors and the interconnected nature of the management process (Nigussie *et al.*, 2018; Hurni *et al.*, 2015; Gashaw *et al.*, 2014; Alemu & Kidane, 2014). Furthermore, the fragmentation caused by evolving concepts and sector-oriented planning hinders integrated approaches, with agriculture, forestry, and water resources often operating in isolation and neglecting their interconnections (Brooks *et al.*, 1991; Wang *et al.*, 2016). There is also a lack of research addressing practitioners' perspectives on how watershed management relates to rural development and food security (Mulugeta, 2015). Addressing these challenges is vital for advancing watershed management to enhance food security and rural development. This study aims to examine stakeholder perspectives and analyze the institutional framework for watershed management in Qarsa Woreda, East Hararghe Zone, Oromia Regional State, to address the gaps between theoretical frameworks and practical implementation, ultimately aiming to improve food security outcomes.

2 Methodology of the Study

2.1 Description of the Study Area

The study was conducted in Qarsa Woreda, which is situated in the East Hararghe Zone of the Oromia Region in Ethiopia. Geographically, the Woreda is located between latitudes 9^o17' and 9^o29'N, and longitudes 41^o12' and 41^o56'E to the west. The district experiences a bimodal rainfall pattern characterized by an average annual rainfall of 1225 mm/year. The annual mean minimum and maximum temperatures are recorded at 12.5^{o}C and 26.6^{o}C, respectively. The rainy seasons include Belg (Arfasa) from March to May and Kiremt (Gana) from June to September, with a dry season prevailing from October to February (Qarsa Woreda Agriculture Office, 2022).

Agriculture forms the backbone of the rural economy in Qarsa Woreda, predominantly practiced under rain-fed conditions. The agricultural system is characterized by mixed crop-livestock production, with maize (*Zea mays* L.) and sorghum (Sorghum bicolor) serving as staple crops. Additionally, khat (*Catha edulis*) and coffee (*Coffea arabica*) are important cash crops cultivated in the area. Watershed management strategies have been implemented over an extended period through various initiatives such as Free Mass Mobilization (FMM), Sustainable Land Management Program II (SLMPII), and Productive Safety Net Public work (PSNP_PW). However, despite these efforts, the Woreda continued to face significant challenges related to chronic food and nutrition security, soil erosion, soil infertility, and water stress.

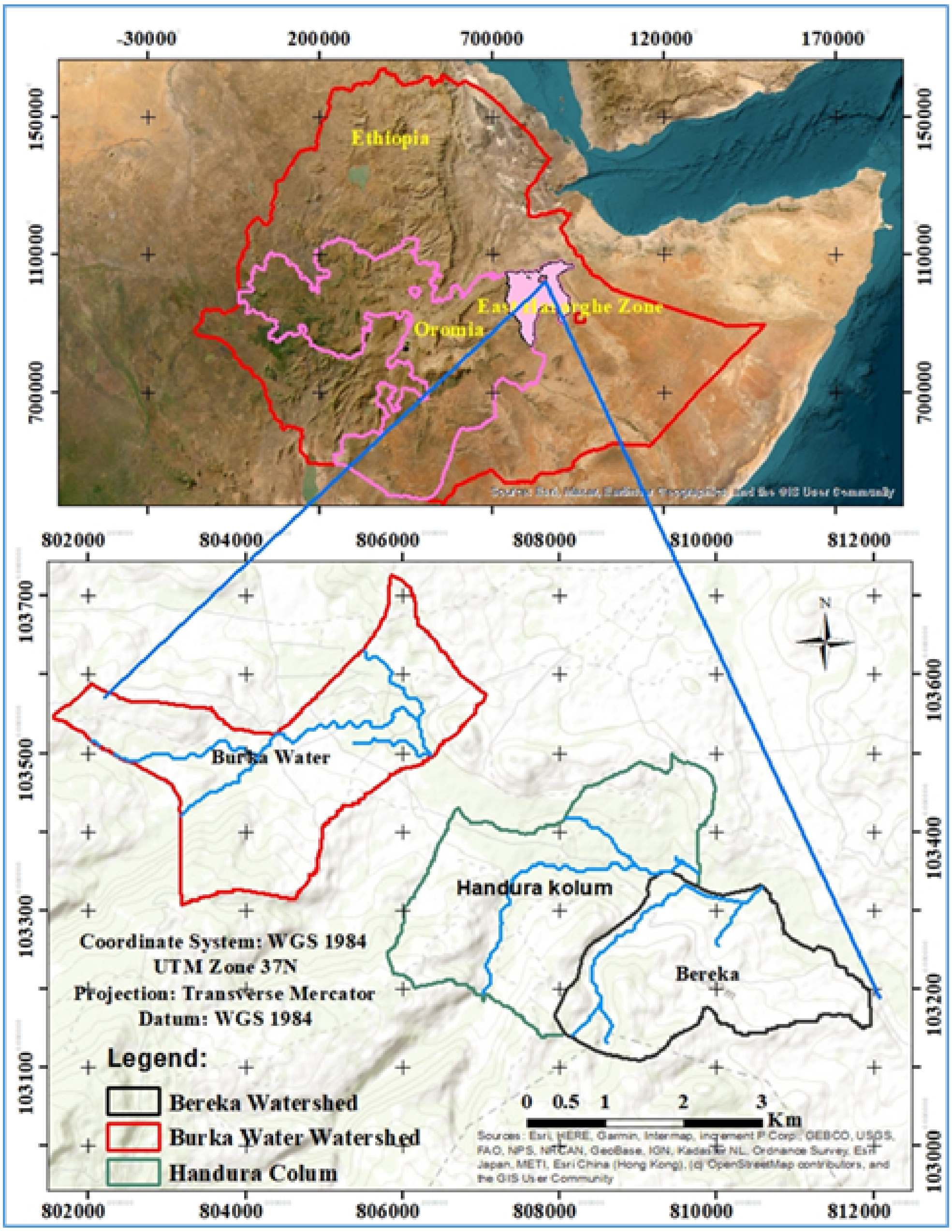

Figure 1. Map of the study area

2.2 Sample design and data collection methods

The study focused on these micro watersheds (Figure 1). Specifically, the Free Mass Mobilization program was a government initiative that did not receive any external funding support. Conversely, the Sustainable Land Management Program and Productive Safety Net Program were funded by external sources. Despite their differences, all three programs adhered to the same watershed management guidelines and shared a common objective: promoting sustainable natural resources management and enhancing ecosystem health to improve food security. This unified objective underscores their commitment to addressing local challenges such as soil erosion, soil infertility, and water stress, and other related watershed management activities for livelihood improvement.

The study utilized a mixed-methods approach, combining quantitative data collection through a household survey with qualitative data from focus groups and key informant interviews (following Creswell, 2003). The study area, Qarsa Woreda, was purposefully selected due to the presence of free mass mobilization, a sustainable land management program, and a productive safety net program simultaneously. The micro watershed was selected based on specific criteria, such as sites adjacent to each other, historical similarity of watershed management interventions, similar land use systems, and soil and water conservation practices. Based on this, one micro watershed from each program approach was selected. Respondent households were selected using a sample size determination method outlined by Kothari (2004), which typically involves statistical calculations to determine the minimum number of respondents needed for the survey to achieve valid results.

$$S = \frac{Z^2 * P * (1 - P)}{C_2} \tag{1}$$

Where: Z = Z-value (1.96) for 95 confidence level
P = is the percentage picking a choice, expressed as a decimal (0.5)
C = is the confidence interval expressed as a decimal (0.05 = $\pm$0.05)

Subsequently, the actual sample size for the study area was determined as:

$$SS_{pk} = \frac{S}{1 + \frac{S-1}{P_k}} \tag{2}$$

Where: SS_{kp} is the sample size for the known population size
S is the sample size for the unknown population calculated using Equation 1
P_k is the known population size from which the sample size is calculate

Then a total of 337 individuals were randomly selected from the total population in three micro watersheds: 118 (35%) from Baraka, 107 (31.8%) from Burka Watter, and 112 (33.2%) from Adhura Kosum (Table 1). Additionally, 63 professionals and managers were selected based on their expertise, organizational roles, and current involvement in watershed management.

Table 1. The maximum likelihood estimates of the logistic regression model

No.	Name of micro watershed	Program approach	Area in Ha	Population	
				HH	Sample size
1	Andhura Kosum Micro watershed	Free Mass Mobilization	759.5	734	112
2	Baraka Micro watershed	PNSP-PW	565.7	639	107
3	Burqa Water micro watershed	SLMP-II	853.1	765	118
			2178.3	2138	337

(Sources: Data from '*kebele*' administration and development agent)

The selection process involved individuals from different levels: 9 from the federal level, 14 from the regional level, 13 from the zonal level, 14 from the Woreda level, and 13 from the kebele level. Furthermore, five focus group discussions were conducted at various government levels and within the three micro watersheds. Each group consisted of 7 to 9 members selected based on their knowledge, gender, age, experience, educational background, social status, and understanding of watershed management and community participation.

In addition, before starting the study, a log sheet was designed to track daily activities related to watershed management in two zones, two districts, and six kebeles. The log sheet recorded the activities of experts and development agents involved in watershed management, documenting their experiences, challenges, and achievements. Its main goal was to assess the effectiveness of current practices and the knowledge level of local experts and development agents in watershed management. Analysis of the information revealed that the activities did not align with the core principles of watershed management, indicating a lack of understanding among participants. The analysis of results from the log sheet framework was adjusted to align with the research goals, relevant literature (Meierdiercks *et al.*, 2024; Wang *et al.*, 2016), community-based participatory guidelines (Desta *et al.*, 2005; MoA, 2020), and practical field experience to assess the holistic comprehension of watershed management practices. Additionally, Förch and Thiemann's (2004) components of watershed management were employed to compare the daily recorded activities in the log sheet. Subsequently, three key concepts were identified as crucial benchmarks for evaluating stakeholders' understanding and perspective on watershed management practices. These include:

- Watershed as a physical soil and water conservation concept,
- Watershed as a natural management concept, and
- Watershed as a holistic approach to rural development concept.

2.3 Data Analysis

The data gathered from surveys conducted in households, by professionals, and through focus group discussions were carefully organized and inputted into SPSS 26 for analysis. Basic descriptive statistics such as mean, standard deviation, and frequency were used for presentation. Methods of discourse analysis were used to further explore the developing trends and patterns. The institutional capacity data analysis involved both subjective and objective interpretations.

3 Results and Discussions

3.1 Socio-demographic characteristics of the household and professionals

3.1.1 Socio-demographic characteristics of the household

This section provides an overview of the characteristics of farm households.

Table 2. Socio-demographic characteristics of households

Variable		Frequency	Percent
Sex of the household	Male	294	87.2
	Female	43	12.8
Age of farmer HHS	18-30	66	19.6
	31-45	144	42.7
	46-64	114	33.8
	> 64	13	3.9
Educational level HHs	Cannot read & and write	191	56.7
	Read and write	52	15.4
	Primer (1-4)	29	8.6
	Secondary (5-8)	43	12.8
	Complete (9-12)	22	6.5

Sources: 2021-2022 survey

The data reveals that the majority of participants (87.2%) belonged to male-headed households, while 12.8% were from female-headed households. In terms of education, 56.7% had no formal education, while 15.4% had basic literacy skills, 15.4% were in primary education, 8% were in secondary school, and 6.5% had completed grade 9. The average age of the participants was calculated to be 41.2, with a standard deviation of 11.35 (Table 1). The characteristics of farm households surveyed in this study indicate a predominantly male-headed, low-educated, middle-aged population engaged in subsistence farming. Thus, capacity building measures need to be adapted to enhance the watershed management practices for the livelihoods and food security improvement.

3.1.2 Socio-demographic characteristic professionals

Table 2 provides a detailed summary of the socioeconomic characteristics of the professional individuals included in the study. The data shows a significant gender imbalance in professional roles, with the majority of respondents being male (84.7%). Additionally, a large number of participants had extensive professional experience, with over half having more than 10 years of experience (55.1%). This suggests that the survey included a group of professionals with a wealth of experience. In terms of education, most participants held a bachelor's degree (59.7%), while only a small percentage had a certificate (1.4%).

Table 3. Descriptive statistics of professionals respondent characteristics

Characteristics	Groups	Frequency	Percent
Sex of the respondent	Male	61	84.7
	Female	11	15.3
Government hierarchy level	Federal level	12	16.7
	Regional level	16	22.2
	Zone level	15	20.8
	Woreda level	16	22.2
	Kebele level	13	18.1
Age of the respondent	(20-29)	8	11.1
	(30-39)	40	55.6
	(40-49)	18	25.0
	Above 50	6	8.3
Organizational position	DA	9	12.5
	Supervisor	2	2.8
	Expert	24	33.3
	Team leader	27	37.5
	Manager	10	13.9
Work Experience	1-5	19	26.4
	6-10	13	18.1
	Above 10	40	55.5
The educational level of the respondent	Certificate	1	1.4
	TVET/Diploma	7	9.7
	Degree	43	59.7
	MSC	21	29.2

Sources: 2021-2022 survey

The survey also ensured a diverse representation of government levels, allowing for a comprehensive understanding and effective resolution of relevant issues.

3.2 Knowledge and perception on integrated watershed management among professionals

Over the past decade, watershed science has faced significant scientific and technical challenges that have shaped current integrated watershed management strategies for rural development (Wang *et al.*, 2016; Gopa, 2021). Our survey results reveal notable variations in how professionals perceive integrated watershed management: 54% primarily view it as natural resource management, 36.5% interpret it as rural development, and 9.5% see it mainly as soil and water conservation (Figure 2). This discrepancy indicates a lack of consensus and suggests an incomplete understanding of the watershed concept among professionals. The observed variations underscore a challenge in achieving a unified approach to watershed management. The diversity in perceptions highlights the need for conceptual frameworks and agreement on the principles and implications of integrated watershed management. This finding is consistent with Meierdiercks *et al.* (2024), who observed that 96% of definitions describe a watershed merely as a geographical region, with only 35% linking it to terms such as river basin, drainage basin, or catchment, and just 7.8% incorporating human activities. Similarly, Meshesha and Tripathi (2015) emphasized that despite ongoing efforts to advance watershed management for sustainable rural development, the conceptualization of the approach remains problematic.

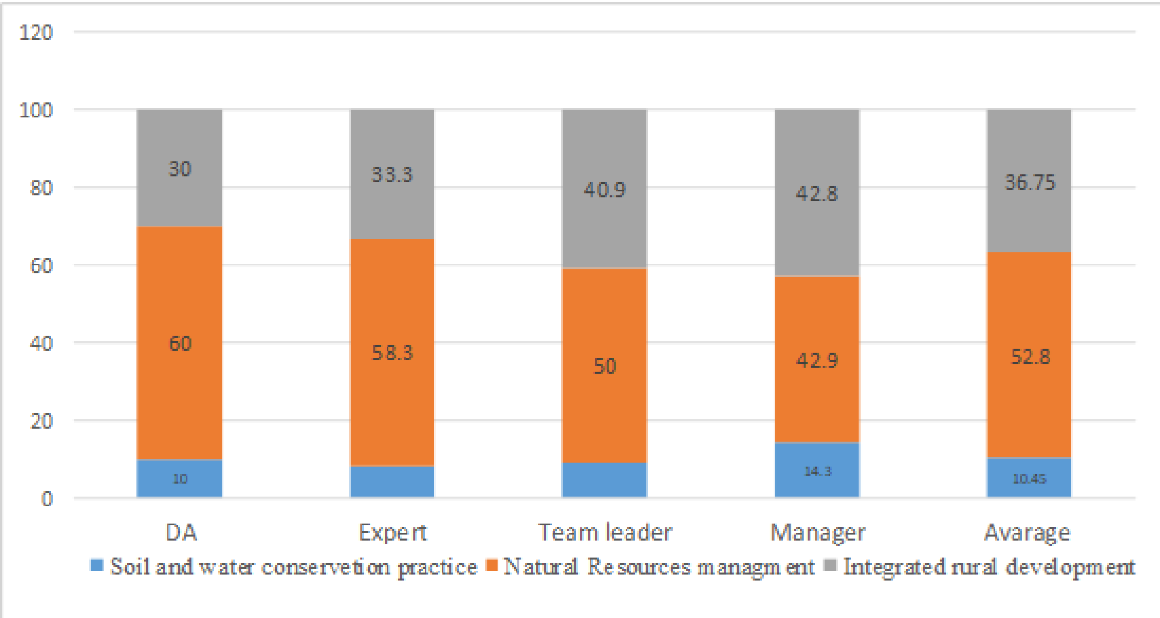

Figure 2. Perceived meanings and understanding of watershed development by professional (Sources: 2021-2022 survey)

Stakeholders' perception and understanding of the watershed management concept were also assessed using factors such as type of organization, work experience, field of study, organizational hierarchies, organizational positions, and educational level (Table 3). The chi-square test revealed that the type of organization, work experience, and field of study significantly impacted stakeholders' understanding of the concept, with P values of 0.016, 0.031, and 0.002, respectively. Interestingly, positions within an organization and educational background demonstrated similar comprehension and perception of the watershed management concept. Individuals with expertise in natural resources or related fields showed a greater understanding of watershed management than those from different backgrounds. This implies that watershed management is often seen primarily as part of natural resources management rather than a sustainable approach to rural development. Similarly, individuals working in agriculture had a better grasp of watershed management than those in other sectors, suggesting that other organizations may not see watershed management as a viable strategy for rural development. Furthermore, the significant associations found in this study emphasize the need for tailored approaches and targeted interventions to enhance stakeholders' comprehension of this concept, particularly for those with different organizational affiliations, work experiences, and academic backgrounds.

Table 4. Knowledge and understanding of professionals about watershed management at different level (N=63)

Group	Soil and water conservation practice (%)	Natural Resources management (%)	Integrated rural development (%)	Chi-Square	Df	P-Value	SF level
Type of organization affiliation	18.9	55.3	25.8	24.746	12	0.016	SN
Organizational hierarchy	5.93	54.03	40.04	7.228	8	0.512	NSF
Organizational position	5.43	45.79	48.77	5.404	8	0.714	NSF
Work Experience	6.1	60.8	33.1	10.604	4	0.031	SF
Field of study (professions)	3.85	57.22	38.93	20.819	6	0.002	SF
Educational level	2.56	67.53	29.9	4.809	6	0.569	NSF
Overall	7.13	56.78	36.09				

Sources: 2021-2022 survey

3.3 2.6 Knowledge and perception of farmers about watershed management

Regarding the knowledge and understanding of the local community, the study's findings revealed that the perception of watershed management varied among the local community. About 17.8% of farmers involved in SLMP II micro watershed, 11.9% in PNSP_PW, and 8.9% in community mass mobilization micro watershed considered watershed management as a rural development approach, while the majority of the respondents viewed it as natural resources management and soil and water conservation (Table 2). This indicated that a limited number of individuals within the community perceived it as a means to enhance economic progress and improve the standard of living in rural regions. Conversely, the majority of farmers predominantly regarded it as a method of environmental preservation, prioritizing it over alternative approaches. The chi-square test's statistical analysis also revealed a significant difference among the three micro watersheds in terms of their performance. Specifically, the micro watershed where participants of the SLMP II program were involved showed significantly better results compared to both the PNSP_PW micro watershed and the free mass mobilization micro watershed (P=0.04).

The findings from the surveyed households and focus group discussions reveal insights into how different groups of farmers perceive watershed management and the associated resources provided by various programs. Farmers involved in PNSP-PW and SLMP II micro watershed projects view the resources and financial aid not as integral components of watershed management but as incentives or compensation for their labor. On the other hand, farmers participating in the free mass mobilization program see watershed management as a government-driven enforcement program that mandates their involvement in activities such as soil conservation work during the dry season and tree planting in the summer months. The varying viewpoints within the three micro watersheds demonstrate the influence of indigenous knowledge and traditions on perspectives regarding watershed management. Farmers' perceptions are primarily influenced by their direct participation in specific projects rather than by institutional frameworks or comprehensive strategies. This narrow perspective prevented farmers from fully understanding the importance of sustainable watershed management practices in promoting long-term environmental health, improved soil fertility, and increased water availability, which are crucial for enhancing food security. The findings align with the research of German *et al.* (2007) and Terefe *et al.* (2015), who noted that differing stakeholder perceptions make it challenging to adopt a holistic watershed management approach. Similarly, Thiemann *et al.* (2018) reported that reliance on traditional methods and strategies poses a significant challenge to holistically implementing watershed management. Linking the financial aid and resources to the broader objectives of watershed management is important rather than viewing them as mere compensation.

Table 5. Knowledge of farmers about watershed management across the three micro watersheds

	Baraka PNSP-PW N=118	Burka Water_SLMP N=107	Adhura kosum_Regular N= 112	Over all N=337	Pearson Chi-Square	Df	P-value
Soil and water conservation	50 (42.4%)	30 (28.%)	52 (46.4%)	132 (39.2%)	9.900	4	0.042
Natural Resources Management	58 (45.8%)	58 (54.2%)	50 (44.6 %)	162 (48.1)			
Integrated rural development	14 (11.9 %)	19 (17.8%)	10 (8.9%)	43 (12.8)			

Sources: 2021-2022 survey

3.4 Knowledge and perception of watershed among professionals and the local community

Figure 3 illustrates the varying perception and knowledge of watershed management across different tiers of government and community levels. At the federal level, approximately 67% of respondents perceived it as a holistic approach to rural development, while 33% saw it as natural resource management. Similarly, at the regional level, 64% considered watershed management a comprehensive rural development, with 36% linking it to natural resource management. This result indicates a consistent perception at the federal and regional levels, with a strong emphasis on watershed management as part of comprehensive rural development. However, opinions diverged significantly at the zone level, with 54% connecting it to natural resource management, 38% to comprehensive rural development, and 8% specifically identifying it as soil and water conservation. At the woreda and kebele levels, the predominant view was that of natural resource management, with 64% and 69% respectively holding this perspective. The community-level survey results displayed a mix of opinions, with 46.6% considering watershed management as natural resource management, 40.7% as soil and water conservation, and only 12.7% regarding it as comprehensive rural development.

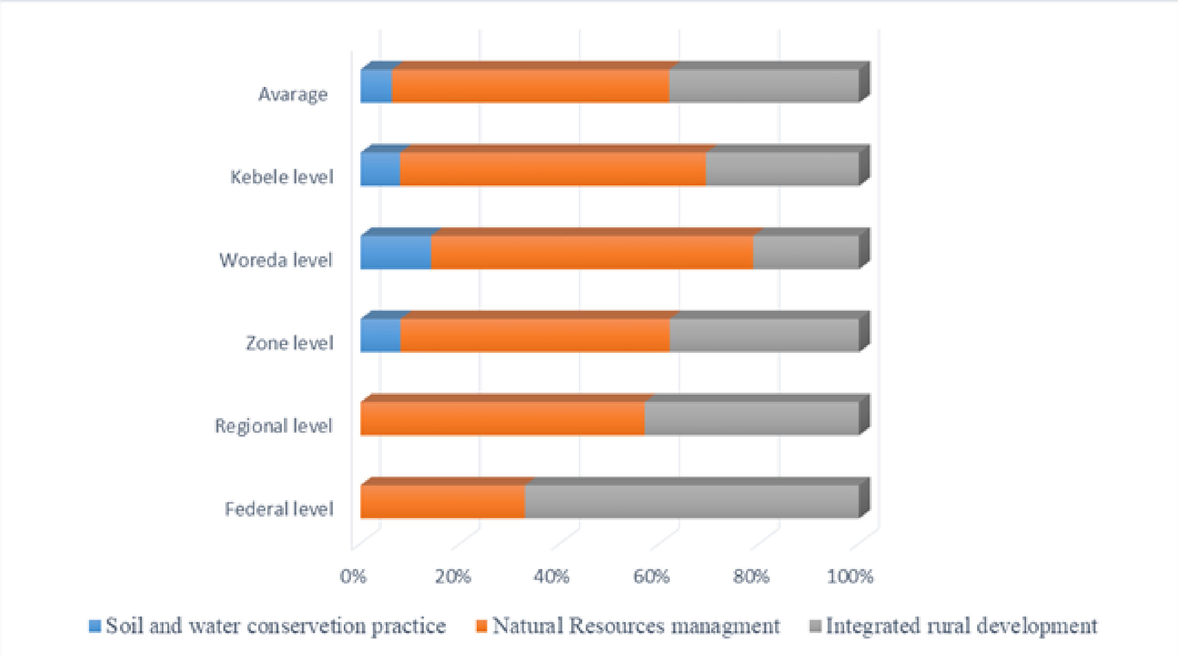

Figure 3. Perceived meanings and understanding of watershed development by different experts across government hierarchies (Sources: 2021-2022 survey)

The study's findings showed a significant difference in the perception of watershed management between government bodies and local communities. The focus group discussions confirmed that the lack of agreement among different levels of governance resulted in significant obstacles and fragmented initiatives, ultimately reducing the effectiveness of watershed management. This lack of unity not only impacts food security but also hinders broader development goals, highlighting the need for a cohesive approach to address current challenges and promote sustainable resource management. Additionally, the study underscored the necessity of enhanced communication among governmental entities, local communities, and other relevant stakeholders engaged in watershed management. This observation aligns with the findings of several studies conducted by Wang *et al.* (2016), Cohen & Davidson (2011), Worku & Tripathi (2015), and Gashaw (2015), which also emphasize that the current approach to watershed management primarily focuses on the physical aspects, rather than adopting a comprehensive approach. Unless there is a collective understanding established at all levels, this trend is likely to persist. Narendra *et al.* (2021) also emphasize the importance of a unified vision and a holistic approach in watershed management. Their study highlights the significance of education as a crucial stepping-stone towards improving watershed management.

3.5 Institutional arrangement for watershed management

This section examines how the three micro-watershed approaches handled watershed management practices at the local level and the institutional structure in place across different governance levels. At the federal level, the Ethiopian Federal Democratic Republic amended Proclamation No. 1263/2021, showing that watershed management responsibilities are divided among the Ministry of Agriculture, the Ministry of Water and Energy, the Ministry of Irrigation and Lowland Areas Development, and the Environmental Protection Agency under the Ministry of Planning. Each ministry has specific duties that contribute to a comprehensive management strategy, including policy formulation, supervision, and coordination of watershed management efforts across the country.

The Oromia Proclamation No. 242/2021 has distributed watershed management responsibilities among various regional bureaus and entities, such as the Oromia Bureau of Agriculture, Oromia Bureau of Land, Oromia Bureau of Irrigation and Pastoral Development, Oromia Bureau of Water and Energy, Oromia Environment Commission, and Oromia Forest and Wildlife Enterprise, as well as their corresponding line departments at the zone and district levels. Each entity has specific duties and responsibilities aimed at a comprehensive management approach, including policy development and implementation, oversight, capacity building, coordination, and on-the-ground execution of watershed management activities across the region and specific areas. At the community level, the kebele administration and development agent are primarily responsible for overseeing watershed management.

Figure 4 illustrates the hierarchical arrangement of watershed management at federal, regional, and community levels in the three micro watersheds. The Ministry of Agriculture (MoA) and the regional line department are responsible for coordinating community-based participatory watershed management, including the Sustainable Land Management Program (SLMP) and the Rural Productive Safety Net Programme (PSNP). However, these two programs have their own organizational structure and staff under the MoA and the Oromia Bureau of Agriculture to carry out the program activities. At the woreda level, there is no separate organizational structure for SLMP-II and PSNP-PW to undertake the program activities. Consequently, the government structure, particularly the woreda agriculture office, assumes the responsibility for managing watersheds and takes on the coordination role. At the local level, the Kebele Administration and the community-based watershed committee are primarily responsible for overseeing the management of the three micro-watersheds.

Despite the structured framework for watershed management established across various government hierarchies, the household survey indicated significant gaps in the participation and coordination of federal and regional entities at the village level (see Figure 5). A majority of participants (approximately 97% in the mass mobilization program, 94% in PNSP-PW, and 78% in SLMP-II) expressed dissatisfaction with the lack of support from federal and regional authorities, as well as the inconsistent monitoring and evaluation of the program at the village level. Furthermore, the Development Agent (DA) and district-level experts interviewed emphasized that the decentralization process has not fully empowered local authorities to effectively plan and allocate budgets based on their criteria to address the needs of their communities.

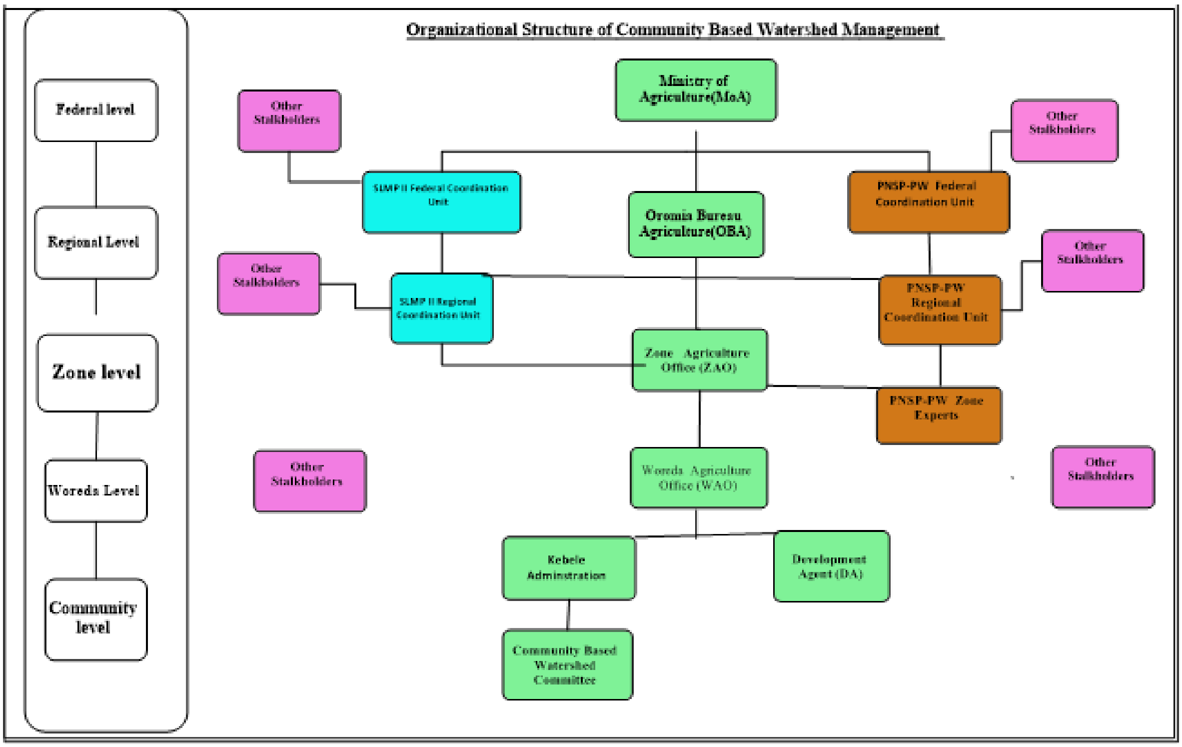

Figure 4. PSNP, SLMPII, and free mass mobilization's institutional arrangement (Sources: constructed by authors)

This finding reveals conflicting perspectives on attributing the main challenges in watershed management solely to local government and community involvement. Instead, the success or failure of a specific integrated watershed management strategy relied on the engagement of higher-level government authorities and their commitment to their responsibilities (Nigussie *et al.*, 2018; Abuto,.2009).

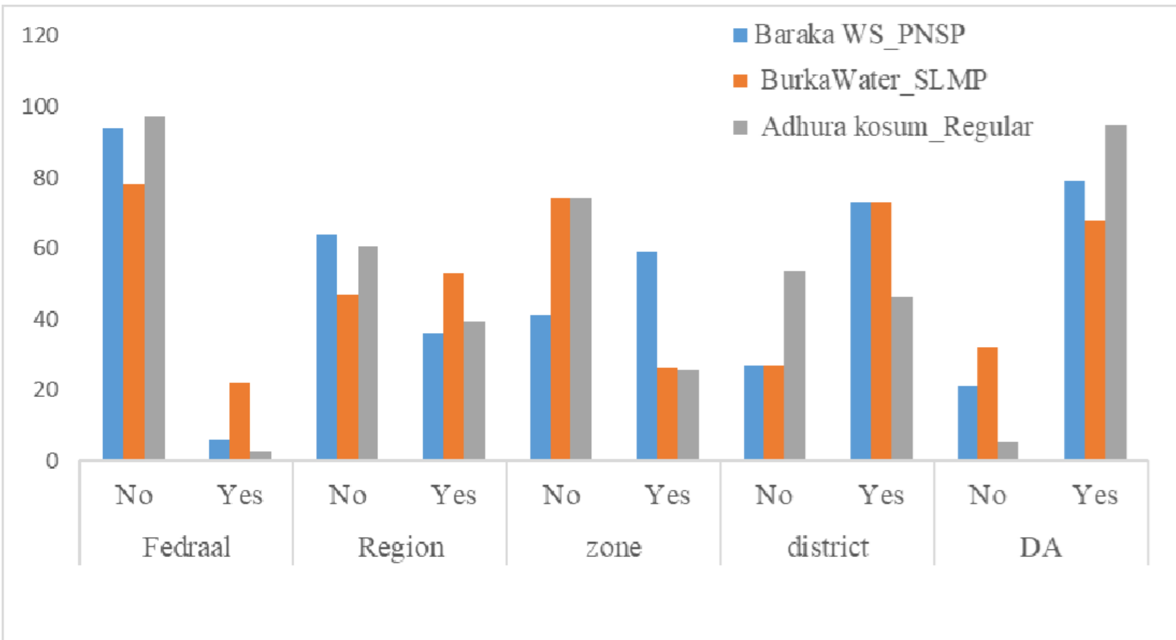

Figure 5. Farmer feedback on government support for watershed management in three micro watersheds at the community level

The findings from the survey underscore the existence of well-organized watershed committees in the three micro watersheds as a positive aspect of the initiatives. Nevertheless, respondents from the three program approaches and woreda-level experts have reported that there is a lack of transparency in the selection of watershed management committee members, which was predominantly made by the political leaders and Development Agents (DAs), as indicated in Figure 6. Focus group discussions also criticized the selection process at both kebele and woreda levels, with political leaders and development agents having a significant influence. They further explained that, despite this, the SLMP II program approach is better at involving the community in the selection process of committee members than the PNSP-PW and Free Mass Mobilization. However, none of the program approaches followed the watershed management guidelines during committee selection or any watershed management process.

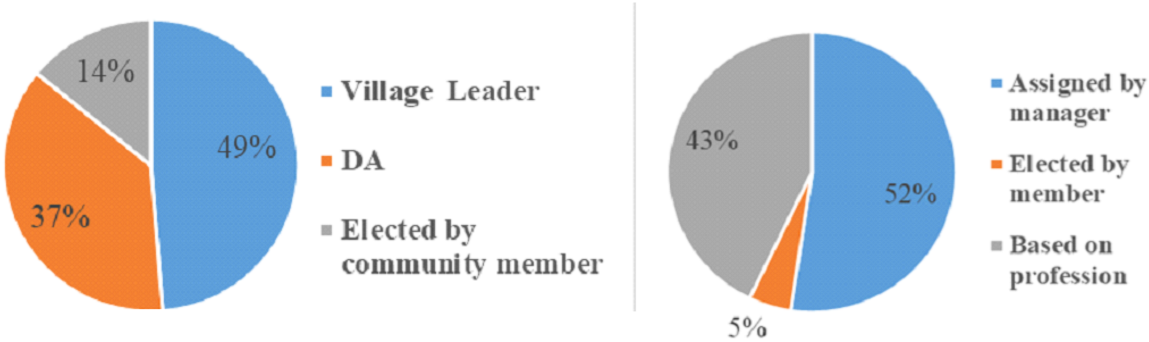

Figure 6. Kebele and Woreda watershed committee selection approach as indicated by the participate respectively

Watershed management at the local level involves not only formal strategies but also informal systems that rely on community-based organizations, traditional leaders, religious leaders, established regulations, and cultural norms. However, interviews with the Focus Group discussions in all three program approaches have revealed that the importance of informal institutions has been declining over time as the government structures have taken over their responsibilities. These interviews have also unveiled that this transition towards formalization in watershed management has led to the loss of traditional knowledge, cultural practices, and community unity, which have been vital in different environmental and social aspects. The study also reveals that government structures may not always be as responsive or adaptable to local needs and conditions as informal systems and lack practical application on the ground at the local level. Almost all of the watershed committee members in the three micro watersheds indicated that the institution lacked practical application on the ground and was politically affiliated, which affected the community participation in decision-making, planning, implementation, and evaluation of watershed practices.

However, the success of an integrated watershed management approach depended on the involvement of government authorities at all levels and the local community. The finding aligns with Gashaw *et al.* (2014) emphasis on the importance of inclusive community institutions in reducing poverty. Kidane *et al.* (2014) also highlighted the role of local institutions in conserving natural resources at the community level. Other studies by Nigussie *et al.* (2018) and Bekele *et al.* (2023) have also shown that the success or failure of integrated watershed management strategies relies on the participation of higher-level government authorities and their dedication to their duties. This study suggested creating transparent and accountable multi-stakeholder platforms to enhance communication and collaboration among government agencies, local communities, and other stakeholders that consider the interests and concerns of local communities in watershed management.

Partnership and stakeholder coordination in Watershed Management

The success or failure of watershed management may depend on the degree of responsibility that partners feel for cooperation and coordination. The study assessed variables influencing collaboration and coordination among stakeholders at various government levels. Figure 7 provides a visual representation of the feedback from respondents at each government level, highlighting how these factors are perceived across different tiers of government.

Furthermore, respondents from the SLMP-II and PNSP-PW projects at the federal and regional levels reported that, despite having formal platforms for the technical and steering committees for planning, implementation, monitoring, and evaluation of watershed management activities, coordination and integration were notably weak or even nonexistent due to the lack of effective accountability mechanisms. In the context of free mass mobilization, experts and managers at the federal and regional levels indicated that there was no collaborative platform. Instead, each ministry, organization, and department operated with its own separate plan. This lack of integration was also confirmed by experts at the zonal and woreda levels, who observed that watershed management planning was largely sector-based, driven by top management directives. Development agents further highlighted that, although the planning process is intended to be bottom-up, it frequently takes place at higher levels and is then handed down to lower levels. Kebele watershed committees shared this perspective, emphasizing their limited knowledge and understanding of coordination and integration, which are crucial for effective watershed management.

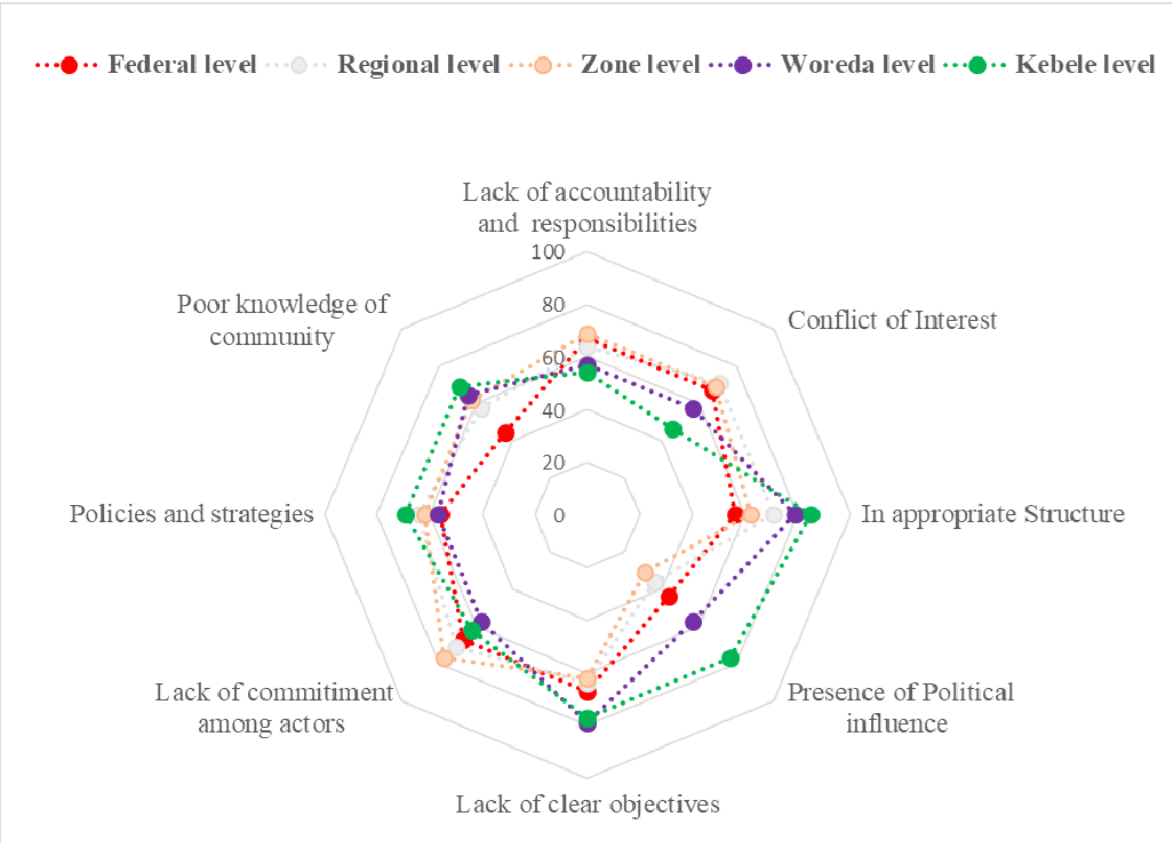

Figure 7. Factor influencing coordination in watershed management across government hierarchy (Sources: 2021-2022 survey)

The study on three micro watersheds has shown that, despite the existence of formal platforms for technical and steering committees responsible for the planning, implementation, monitoring, and evaluation of watershed management activities at different levels for SLMP-II and PNSP-PW, and at the woreda and kebele levels for the free mass mobilization micro watersheds, there is a significant lack of coordination and integration due to the ineffective accountability mechanisms in place across all three watersheds. Moreover, the watershed management practices across all three micro watersheds studied are not aligned with the specific laws and guidelines established for each watershed. This observation is consistent with the FAO (2017) study, which indicated that the absence of accountability mechanisms negatively influences the effectiveness of promoting collaborative actions within watershed management. Similarly, research by Berardo *et al.* (2019) and Abiye (2019) reported that the lack of proper coordination results in ineffective watershed management. Many experts also concur that "sectoral ego" contributes to the lack of coordination, leading to fragmented interventions that fail to produce cumulative positive impacts. Further supporting this view, Bantider *et al.* (2020) examined eight policy documents and sixty-three laws enacted post-1990s related to natural resource management and found that these policies did not achieve the intended outcomes largely due to ineffective implementation and inadequate communication with local stakeholders.

3.6 Watershed management capacities for food security

The study explored how watershed management can improve food security by examining factors such as water availability, soil fertility, and agricultural practices from the perspective of household perceptions. A majority of participants (72.3%) in the mass mobilization programs, including PNSP-PW (75.4%) and SLMP-II (78.5%), reported an increase in crop yield as a result of the continuous implementation of watershed-based physical and biological soil and water conservation measures. These findings remained uniform across the three micro watersheds under investigation. Additionally, households mentioned seeing improvements in water availability, animal feed, and income opportunities due to these practices. Figure 8 shows a summary of the improvements reported by households in the three programs in detailed data.

These findings align with Degefa's (2005) definition of food security, which describes it as the ability of farmers and pastoralist households to meet their food and essential needs through diverse livelihood activities, including farming, livestock raising, non-farm businesses, or wage labor. Gashaw (2015) also highlighted that integrated watershed management covers various sectors—such as environment, agriculture, forestry, and animal husbandry—with the goal of improving food security. Meanwhile, Danacioglu and Tagil (2019) emphasized the potential of watershed management to enhance agricultural productivity and promote sustainable tourism through the preservation of natural and cultural heritage.

Despite the positive impact of watershed management on food security, the research findings indicate that challenges limit its full potential across the three micro watersheds. One significant challenge is the differing perspectives on watershed management across various levels of government and the community. At the federal and regional levels, it is viewed as integral to rural development. However, at the zonal and woreda levels, opinions vary, with a stronger emphasis on natural resource management. At the community level, there is a mix of viewpoints: some see watershed management primarily as natural resource management, while others focus on soil and water conservation (see Table 2 and Figure 3). Sector-specific planning and a limited understanding of coordination among the watershed committees have contributed to an incomplete recognition of watershed management's transformative potential in enhancing food security. Without addressing these underlying issues, the potential benefits of watershed management may not be fully realized.

This aligns with Sayer *et al.* (2013), Moken *et al.* (2015), and System *et al.* (2020), who highlight that a holistic approach to watershed management is crucial for balancing environmental, socio-economic, and political objectives to improve the quality of life for local communities and ensure sustainable management. Additionally, Gashaw *et al.* (2014) and Hurni *et al.* (2015) emphasize the need to bring together various stakeholders, including government agencies, local communities, and others, to develop a shared understanding of the holistic concept of watershed management. The study emphasizes the need for utilizing knowledge-sharing platforms, such as extension services, training programs, and community-based organizations, to adopt a holistic approach to watershed management.

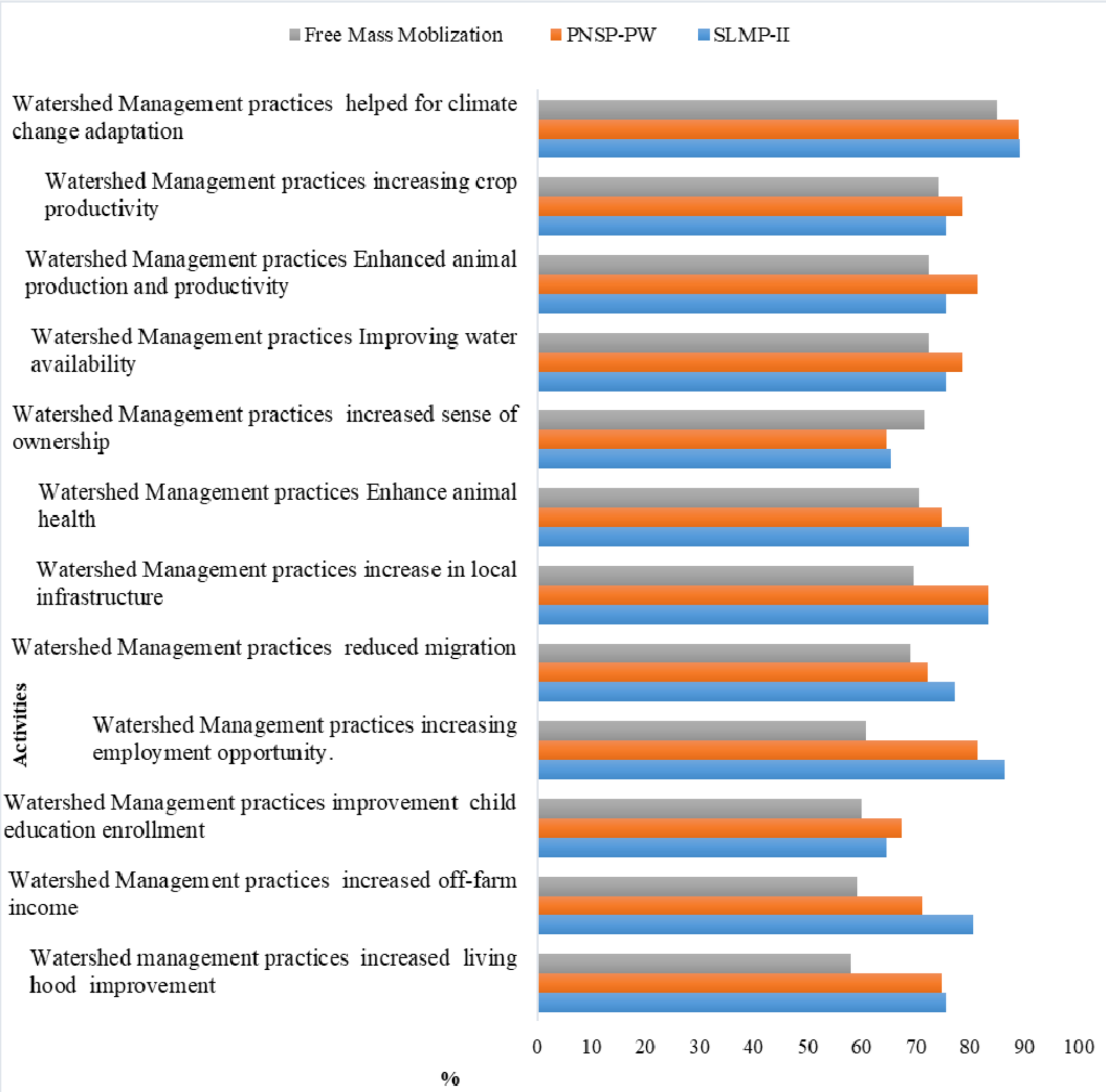

Figure 8. Households' perception on the effectiveness of watershed management practices for food security (Sources: 2021-2022 survey)

4 Conclusion

The study explored how institutional frameworks and stakeholder knowledge influence watershed management and its impact on food security. Findings from three micro watersheds reveal that effective watershed management significantly enhances agricultural productivity, water resource management, employment opportunities, and livestock feed, thereby improving food security. Despite these benefits, there is a notable discrepancy in understanding between professionals and farmers.

Individuals with expertise in natural resources and agriculture exhibit a nuanced grasp of watershed management, aligning their perspectives with the goals of managing natural resources and agricultural productivity. In contrast, professionals from other sectors view watershed management as peripheral to their specific organizational goals. Similarly, participants in the micro watersheds viewed watershed management as isolated measures related only to their specific projects, rather than as an integral part of a broader developmental strategy. This limited perspective, which emphasizes immediate, sector-specific benefits over the holistic potential of watershed management, obstructs the adoption of a more integrated approach. As a result, this narrow understanding undermines the effective implementation of comprehensive watershed management strategies, which are essential for maximizing benefits and promoting sustainable rural development.

The study identifies significant issues with stakeholder coordination and accountability, revealing inadequate collaboration both vertically (across different levels of government) and horizontally (among various departments and agencies). Focus group discussions highlight the insufficient involvement of federal and regional experts and managers in providing technical support and conducting regular monitoring and evaluation at the village level across all three micro watersheds. This lack of effective oversight and support from higher authorities poses a risk to the success of watershed management initiatives. Enhanced coordination and active engagement from federal and regional levels are crucial for ensuring comprehensive and effective implementation at the grassroots level.

To optimize the effectiveness of watershed management for food security, it is essential to enhance stakeholder understanding, foster collaborations among government agencies, local communities, and other relevant entities, and strengthen accountability mechanisms. Integrating watershed management into rural development projects, aligning these strategies with local objectives, and securing robust policy support are also critical for success. By addressing these factors and advancing educational initiatives and institutional collaboration, stakeholders can achieve sustainable rural development and improved food security, ensuring long-term benefits for both ecosystems and communities.

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Ethical approval and consent to participate:

The research methods employed in this study adhered closely to the prescribed guidelines and regulations. The research protocol underwent a thorough evaluation by the CoDS (Collage of Developmental Study of Addis Ababa University Institutional Review Board) and obtained ethical approval, as evidenced by the case number 050/03/2023.

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The authors declare no competing interests.

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Data availability statement:

Data will be made available on request.

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