

## 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

Currently, there is a rapidly growing interest in modern clean energy generation in Ethiopia as a means to ensure economic and environmental sustainability. However, there is still a gap in empirical research addressing how investment in modern clean energy determines the development of a green economy in Ethiopia. This study examined the implication of renewable energy on green economy development in Ethiopia, specifically focusing on the relationship between modern clean energy consumption, economic growth, and environmental quality from 1990 to 2022. The study utilized annual time series data from the World Development Indicators (WDI), the Global Carbon Atlas (GCA), and the International Energy Agency (IEA). The auto regressive distributed lags (ARDL) econometric estimation technique was used to analyze the data. The findings revealed that the use of non-renewable energy, biomass, and modern clean energy were significant factors in explaining the variation in carbon dioxide emissions in Ethiopia. However, only contemporary clean energy demonstrated statistical significance in explaining long-term economic growth. The results suggest that the use of green energy sources, such as hydro, wind, and solar energy, can eventually lower carbon emissions while increasing output. It is recommended that Ethiopian authorities prioritize the promotion of renewable energy sources to prevent the economy from becoming more carbon-intensive in the future. This requires strong collaboration among policymakers, the government, and international cooperation organizations to boost investment in modern clean energy and ensure environmentally and economically sustainable development.

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

### 1 Introduction

Ethiopia, one of the least developed nations in the world, has recently experienced a significant increase in economic output and is among the fastest-growing economies globally. According to available data, Ethiopia had a remarkable growth performance, posting an average annual growth rate of 9.3% from 2013 to 2018, which was impressive (NBE, 2020). This expansion was largely driven by rising industrialization and urbanization, which were in turn fueled by increased energy use (Teka *et al.*, 2020).

Ethiopia aims to achieve middle-income status by

2025, building on its recent record of strong economic growth. Achieving this goal will primarily depend on increasing the productivity of the agricultural sector, expanding the industrial base, and promoting growth in international trade, as outlined in the Growth and Transformation Plan (GTP) (FDRE, 2011). In other words, the desire for industrialization, especially heavy industrialization, results in more energy-intensive economic activities as the country works towards reaching middle-income status.

It is widely recognized that energy infrastructure is a crucial factor influencing a nation's economic ex-

pansion and advancement, often referred to as the lifeblood of the modern economy (Kulionis, 2013). Energy is a major production input and plays a vital role in a country's economic and social development, as it increases the productivity of other factors and improves living standards.

However, according to Kulionis (2013), the rising demand for energy to fuel economic activities also contributes to worsening environmental conditions. Excessive energy usage releases substantial amounts of carbon dioxide, which has been identified as the primary contributor to global warming and climate change.

Demand for energy has recently increased in Ethiopia in line with the country's growing industrialization and rapid demographic expansion. In other words, the country's economic and population growth have driven a significant surge in energy consumption.

According to statistics from the International Energy Agency report (2020), Ethiopia's total final energy consumption rose from 16,771 KTOE in 1990 to 40,717 KTOE in 2018, reflecting a 142.78% increase. This indicates that Ethiopia's energy demand has been rising in close correlation with the country's economic and population growth.

Despite the growing energy needs, Ethiopia's energy consumption structure is inefficient, polluting, and predominantly dominated by biomass energy sources, which account for around 88% of total consumption (MoWE, 2012). Given this energy consumption pattern, the projected increase in energy demand is likely to exacerbate the country's environmental degradation.

Recognizing these challenges, and following the advice of environmentalists and economists to shift growth targets from conventional economic expansion to more environmentally conscious and sustainable development, as stated by Alam *et al.* (2016), Ethiopia has implemented the "Climate Resilient Green Economy (CRGE)" strategy. The aim is to protect the nation from the adverse impacts of global warming and transition towards a green economy.

In this strategy, Ethiopia declares its intention to

achieve middle-income status by 2025 while simultaneously preserving environmental quality (FDRE, 2011). This reflects the country's commitment to pursue economic advancement in a more sustainable manner.

Given Ethiopia's location in a tropical region and the abundance of opportunities for modern environmentally friendly energy sources, the government intends to develop clean energy, specifically hydropower, wind, geothermal, and solar power, as well as non-renewable and combustible renewables and waste. The goal is to realize Ethiopia's ambition of establishing an environmentally conscious 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.

To develop effective policies, a deeper understanding of the causal relationships between renewable energy, economic growth, and the state of the environment is necessary. 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.

For an extended period, numerous economic re-

search studies have examined the relationship between environmental conditions and some of its root causes in both wealthy and poor nations. Since the pioneering work of Grossman and Krueger (1991), several investigations have explored the interplay between environmental degradation and economic activity (including Wolde (2015) and Hamilton & Turton (2002)).

Additionally, various studies (Zakarya *et al.*, 2015; Wolde *et al.*, 2016; Kebede, 2017) have focused on the association between environmental quality, economic activity, and overall energy consumption. Some recent empirical works have also examined the disaggregated effect of conventional and modern energy use on environmental quality, as measured by carbon dioxide emissions (e.g., Jebli and Youssef, 2015).

However, to the best of the researchers' knowledge, no study has specifically examined the impact of renewable energy, particularly modern clean energy, on green economic development. 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 moving the country's energy consumption structure toward modern clean energy actually assist it to accomplish the goal of the Climate Resilient Green Economy (CRGE) strategy by 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 analyzed the effect of renewable energy, particularly modern clean energy consumption, on green economy development in Ethiopia using annual time series data spanning 32 years, from 1990 to 2022. This time frame was selected to ensure the availability of appropriate data for the investigation.

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

### 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.

In light of this, the model proposed in this study, which has the following form, appears to be consistent with the broader literature on the determinants of carbon dioxide emissions:

$$CO_2 = f(EC_t) \quad (1)$$

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

However, this generic model is not fully aligned with the goal of the current study. Since the objective of this investigation is to examine the influence of the current use of clean energy on environmental quality, as measured by carbon dioxide emissions, the energy use variable in the aforementioned model needs to be further decomposed.

Specifically, the energy use variable ( $EC_t$ ) in Equation (1) should be subdivided into three components: modern clean energy use ( $MCE_t$ ), non-renewable energy use ( $NRE_t$ ), and biomass energy use ( $BE_t$ ). 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.

As a result, the following reduced-form model is proposed to assess the potential environmental impact of the variables of interest:

$$CO_2 = f(MCE_t, NRE_t, BE_t, GDPP_t, POP_t, UPG_t) \quad (2)$$

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 for population at period  $t$ , and  $UPG_t$  stands for urbanization at period  $t$ .

According to Equation (2), the use of modern clean energy, non-renewable energy, biomass energy, real GDP per capita, population, and urbanization can all be environmental determinants in Ethiopia.

**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:

$$Y = f(K, HK, LF, A) \quad (3)$$

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.

The rationale for including these additional energy variables is to mitigate the risk of omitted variable bias and to investigate their comparative impact on the country's economic growth. As a result, the final growth model is specified as follows:

$$GDPP_t = f(K_t, HK_t, MCE_t, NRE_t, BE_t) \quad (4)$$

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.

Finally, for estimation purposes, all the variables in the equations were transformed into their logarithmic forms. This transformation offers several benefits. First, it reduces the volatility in the data series or the impact of potential outliers and large coefficients. Second, it enables the capture of growth effects or the determination of approximate growth rates. The coefficients are then interpreted as elasticities.

Elasticities 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:

$$\ln CO_{2t} = \theta_0 + \theta_1 \ln MCE_t + \theta_2 \ln NRE_t + \theta_3 \ln BE_t + \theta_4 \ln GDPPC_t + \theta_5 \ln POP_t + \theta_6 \ln UPG_t + e_t \quad (5)$$

$$\ln GDPPC_t = \alpha_0 + \alpha_1 \ln K_t + \alpha_2 \ln HK_t + \alpha_3 \ln MCE_t + \alpha_4 \ln NRE_t + \alpha_5 \ln BE_t + e_t \quad (6)$$

Where  $\ln$  is natural logarithm,  $e_t$  is disturbance term,  $\theta_s$  and  $\alpha_s$  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:

$$\begin{aligned} \Delta \ln CO_{2t} = & \theta_0 + \theta_1 \ln MCE_{t-1} + \theta_2 \ln NRE_{t-1} + \theta_3 \ln BE_{t-1} + \theta_4 \ln GDPPC_{t-1} + \\ & \theta_5 \ln POP_{t-1} + \theta_6 \ln UPG_{t-1} + \\ & \sum_{j=1}^n \beta_{1j} \Delta \ln CO_{t-j} + \sum_{j=1}^n \beta_{2j} \Delta \ln MCE_{t-j} + \\ & \sum_{j=1}^n \beta_{3j} \Delta \ln NRE_{t-j} + \sum_{j=1}^n \beta_{4j} \Delta \ln BE_{t-j} + \\ & \sum_{j=1}^n \beta_{5j} \Delta \ln GDPPC_{t-j} + \sum_{j=1}^n \beta_{6j} \Delta \ln POP_{t-j} + \\ & \sum_{j=1}^n \beta_{7j} \Delta \ln UPG_{t-j} + U_t \end{aligned} \quad (7)$$

$$\begin{aligned} \Delta \ln GDPPC_t = & \alpha_0 + \alpha_1 \ln K_{t-1} + \alpha_2 \ln HK_{t-1} + \alpha_3 \ln MCE_{t-1} + \alpha_4 \ln NRE_{t-1} + \alpha_5 \ln BE_{t-1} + \\ & \sum_{j=1}^n \beta_{1j} \Delta \ln GDP_{t-j} + \sum_{j=1}^n \beta_{2j} \Delta \ln K_{t-j} + \\ & \sum_{j=1}^n \beta_{2j} \Delta \ln MCE_{t-j} + \sum_{j=1}^n \beta_{3j} \Delta \ln HK_{t-j} + \\ & \sum_{j=1}^n \beta_{4j} \Delta \ln NRE_{t-j} + \sum_{j=1}^n \beta_{5j} \Delta \ln BE_{t-j} + U_t \end{aligned} \quad (8)$$

$\beta_s$  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  $\theta_s$  and  $\alpha_s$  in equations (7) and (8), respectively.  $n$  is the length of the model variables' lag, and  $\Delta$  implies the difference operation.

### 3.4 Estimation procedure

The primary goal of this analysis is to determine if the variables under study have a long-term relationship. To accomplish this, the researchers have utilized unit root tests, such as the Augmented Dickey-Fuller and Phillips-Perron tests, to evaluate the order of integration of each variable. This helps them determine how many times a variable needs to be differenced to achieve stationarity. Once the variables are confirmed to be stationary, the researchers can proceed with regression analysis to make accurate forecasts and conduct policy research.

After the stationarity tests were conducted, the Bound test was employed to establish whether the variables have a long-run co-integrating relationship. Additionally, the researchers performed various model diagnostic tests to ensure the accuracy and stability of the final model. These tests include the functional form test, normality test, serial correlation test, and heteroscedasticity test. The CUSUM and CUSUMSQ tests were also used to assess the model's robustness and stability over time.

## 4 Results and Discussions

### 4.1 Environmental Quality Equation of Ethiopia

To address the issue of spurious regression in time-series data co-integration assessment, it is crucial to properly evaluate the stationarity of the underlying data series. When least squares regression is applied to non-stationary, unrelated datasets, spurious regression is a common occurrence. In such cases, even though the series are unrelated, a significant statistical relationship can be erroneously established. 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 inter-

preting 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

Once the model variables are found to be integrated of order less than two, the ARDL (Autoregressive Distributed Lag) specification can be established, regardless of whether the variables are  $I(0)$  or  $I(1)$  integrated. However, employing the ARDL specification in the presence of  $I(2)$  or higher integrated variables would be inappropriate.

Therefore, this study utilized the standard Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to determine the integration order of the indicators. The optimal lag lengths for the tests were automatically identified using the Schwarz Bayesian Information Criterion (SBIC). The acceptance or rejection of the null hypothesis of the unit root tests, which implies the non-stationarity of the series, was based on the comparison of the test statistics to the critical values and the associated p-values.

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

Variables	Augmented Dickey-Fuller (ADF) and Phillips Perron (PP) Test		
	ADF T-statistics	PP T-statistics	Decision
$\ln CO_2$	0.4329	1.2184	$I(1)$
$D(\ln CO_2)$	-5.7547***	-6.3754***	
$\ln CME$	1.4644	1.5766	$I(1)$
$D(\ln CME)$	-3.6920***	-3.8130***	
$\ln BE$	-4.1908***	-8.3005***	$I(0)$
$\ln NRE$	0.7038	0.8192	$I(1)$
$D(\ln NRE)$	-4.7582***	-4.7582***	
$\ln GDPPC$	2.009	1.7511	$I(1)$
$D(\ln GDPPC)$	-4.1557***	-4.2076***	
$\ln POP$	-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 results of the unit root tests indicate that the environmental quality model comprises indicators with integration order of less than two. This satisfies the necessary precondition for using the bounds testing

approach to cointegration, as developed by Pesaran, Shin, and Smith (2001). Accordingly, the ARDL (Autoregressive Distributed Lag) model is qualified to be employed for assessing the long-term associa-

tions among the variables under consideration.

#### 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
<b>Critical value bounds</b>		
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

To ensure the validity and reliability of the estimation, model diagnostic tests such as 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 employed prior to interpreting the long and short-run elasticities of the environmental quality model. The null hypothesis the tests implies the estimates are reliable and valid.

The model diagnostic assessments are provided in Table 3.

**Table 3.** Model Diagnostics Testing for Environmental Quality Equation

Tests	Method	$\sqrt{F}$ -statistics $\sqrt{\text{Jarque-Bera}}$ 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 )

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.

The assessment can be made by comparing the plots of the test statistics to the critical bounds at the 5% level of significance. If the plots remain within the critical bounds, the null hypothesis of coefficient stability can be accepted.

As shown in Appendix A, the plots of the CUSUM and CUSUMSQ statistics were within the critical bounds at the 5% significance level for the period under consideration. This supports the stability of the coefficients estimated in the environmental quality model.

#### 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.

Table 4 presents the results of the environmental quality model estimation, which includes the estimated coefficients, standard errors, t-values, and probability values.

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

<b>Method: ARDL</b>				
<b>Model selected: ARDL (1, 0, 0, 0, 2, 2, 0)</b>				
<b>Long-run coefficients</b>				
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***
<b>Short-run coefficients</b>				
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)

According to the findings of the environmental quality model, the long-run elasticity of carbon dioxide emissions with respect to modern renewable energy

is -0.234596. This indicates that if all other variables remain constant, a 1% increase in the usage of modern clean energy will result in a 0.234596%



decrease in carbon dioxide emissions in the country under study. 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 finding is consistent with past empirical studies. For example, Adinew M. (2020) found a statistically significant negative association between renewable energy use and anthropogenic carbon dioxide emissions in Ethiopia, supporting the results of the environmental quality model. 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. Furthermore, Uğurlu (2022) found a decreasing effect of renewable energy consumption on  $CO_2$  emissions for the Visegrad Group Countries, including Poland, the Czech Republic, Hungary, and Slovakia.

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.

Nevertheless, the potential benefits of limiting carbon dioxide emissions and boosting environmental quality make this investment worthwhile. Therefore, policymakers and stakeholders must work together to identify strategies for promoting the use of modern clean energy and reducing reliance on fossil fuels. This may involve implementing policies and incentives to encourage investment in modern clean energy, as well as educating the public about the benefits of reducing carbon dioxide emissions.

The long-term findings also imply that increasing the

use of biomass and non-renewable energy sources will exacerbate greenhouse gas emissions and contribute to higher carbon dioxide levels. The long-run elasticity of carbon dioxide emissions is 4.395273 for biomass energy and 0.185574 for non-renewable energy. This means a 1% change in the usage of these energy sources will result in a 4.395273% and 0.185574% change in carbon dioxide emissions respectively.

The significant impact of biomass energy use on anthropogenic carbon dioxide emissions in Ethiopia is noteworthy, as biomass energy contributes to approximately 90% of the country's entire energy mix, according to UNECA (2014). This heavy reliance on wood, wood-derived fuels, and biomass waste consumption, which are classified as primary and environmentally unfriendly energy sources, is a major driver of the increasing carbon dioxide emissions in the country.

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 short-run results of the defined ARDL (1, 0, 0, 0, 2, 2, 0) model, the long-run case is supported by the coefficients of current clean energy, biomass energy, and non-renewable energy use. However, the short-run elasticity of carbon dioxide emissions with respect to modern clean energy utilization is higher than the long-run 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 eco-

conomic 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 indicates that in the short run, there is a direct association among output growth, population, and carbon emissions. Notably, the elasticity of carbon dioxide emissions with respect to population outweighs the effect of output growth, implying that the size of the population adds more to environmental degradation than economic growth. This finding is consistent with the results of a previous study conducted by Shafiei (2013).

Since the short-run output growth elasticity of carbon dioxide emissions is positive, there is no evidence of decoupling of economic growth from carbon dioxide emissions in the near term. However, the long-term insignificant effect of economic expansion on environmental quality could be an indication

of long-term decoupling.

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

The stationarity behavior of the indicators in the economic growth model is presented in Table 5 below. The test results explored that all the indicators are stationary at their first difference, except biomass energy use. This finding qualified the use of the ARDL model for long-term co-integration analysis among the economic growth model variables.

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

Variables	Augmented Dickey Fuller (ADF) and Phillips 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 associa-

tion 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 pres-

ence 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	$\sqrt{F}$ -statistics $\sqrt{\text{Jarque-Bera}}$ 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 be 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

<b>Dependent variable: Real gross domestic product per capita</b> <b>Model selected: ARDL (1, 0, 0, 1, 0, 0)</b> <b>Long-run coefficients</b>				
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
<b>Short-run coefficients</b>				
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.

Further research by Apergis and Danuletiu (2014) for a panel of 80 countries, as well as Shahbaz *et al.* (2020) for a panel of 38 renewable-energy-consuming countries from 1990 to 2018, also found results indicating the importance 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 renew-

ables investment.

In the short run, however, the effect of all other variables on output growth is found to be insignificant. The short-run elasticity of output growth for modern clean energy and non-renewable energy use is 0.194435 and 0.113614, respectively, and is statistically significant in explaining Ethiopia's output growth. 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 en-

ergy 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.

According to the study's findings, modern clean energy sources such as hydroelectricity, wind, and solar have a positive and highly significant environmental impact in Ethiopia. This implies that these energy sources are critical to improving environmental quality by reducing the anthropogenic concentration of carbon dioxide emissions. The study suggests that policymakers and stakeholders in Ethiopia should prioritize the adoption of modern clean energy sources to promote sustainable economic growth and reduce carbon dioxide emissions.

From the study's economic growth model, modern clean energy use has a statistically significant positive impact on Ethiopia's economic growth in both the short and long run. This is because it raises output and contributes to sustainable economic development. In contrast, non-renewable and biomass energy use do not play a significant role in explaining the country's economic growth. These findings suggest that policymakers and stakeholders in Ethiopia should prioritize the adoption of modern clean energy sources to promote sustainable economic growth and development.

## 5.2 Recommendations

Given the study's findings, modern clean energy is a significant contributor to both economic growth and environmental quality in Ethiopia. The study suggests that alternative modern clean energy sources can be a solution to the climate change challenge without posing a threat to Ethiopia's economic growth. These findings highlight the importance of modern clean energy in Ethiopia's green economy development. By prioritizing the adoption of modern clean energy sources, policymakers and stakeholders in Ethiopia can promote sustainable economic growth and development while also addressing environmental concerns.

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 need for strong collaboration among the country's policymakers, government, and international cooperation organizations in boosting modern clean energy investment aiming to ensure that future development is environmentally and economically sustainable. By overcoming these challenges, Ethiopia can promote sustainable economic growth and development while also addressing environmental concerns.

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## Conflicts of Interest

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

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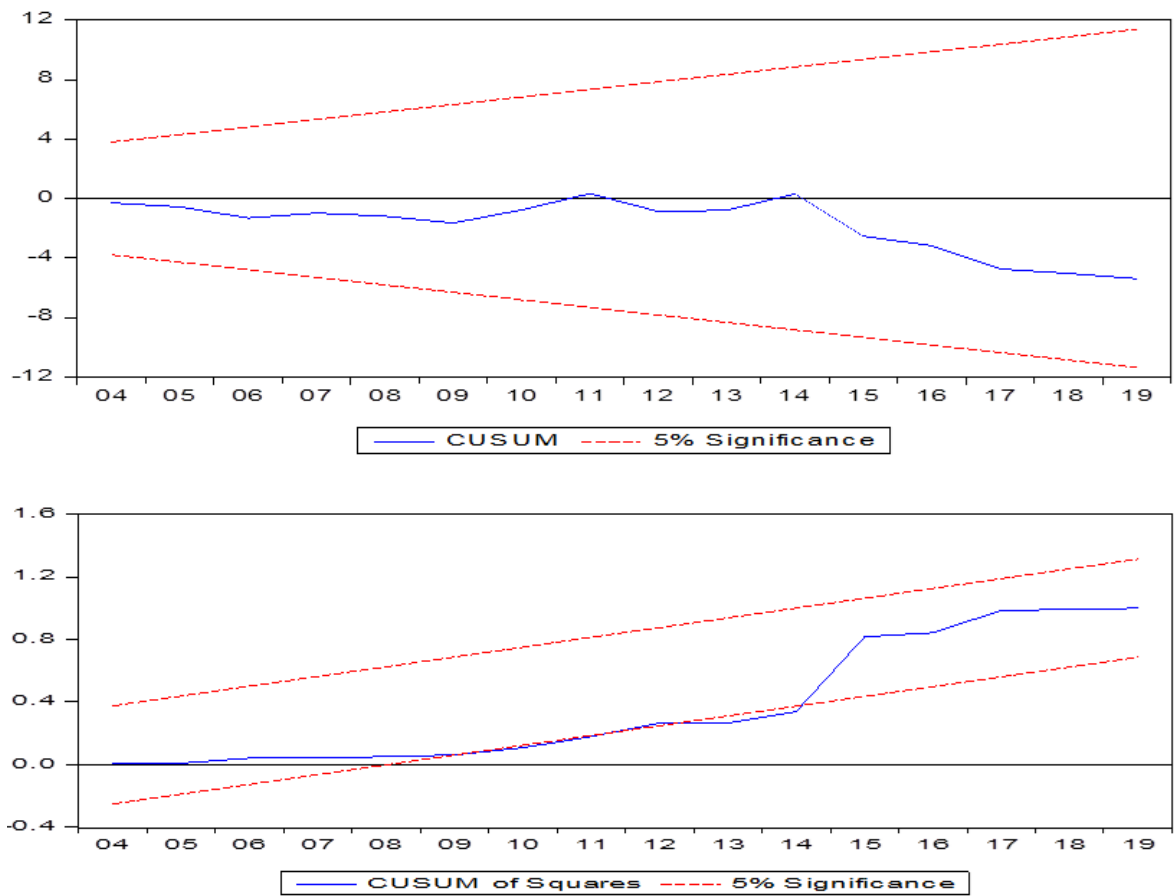
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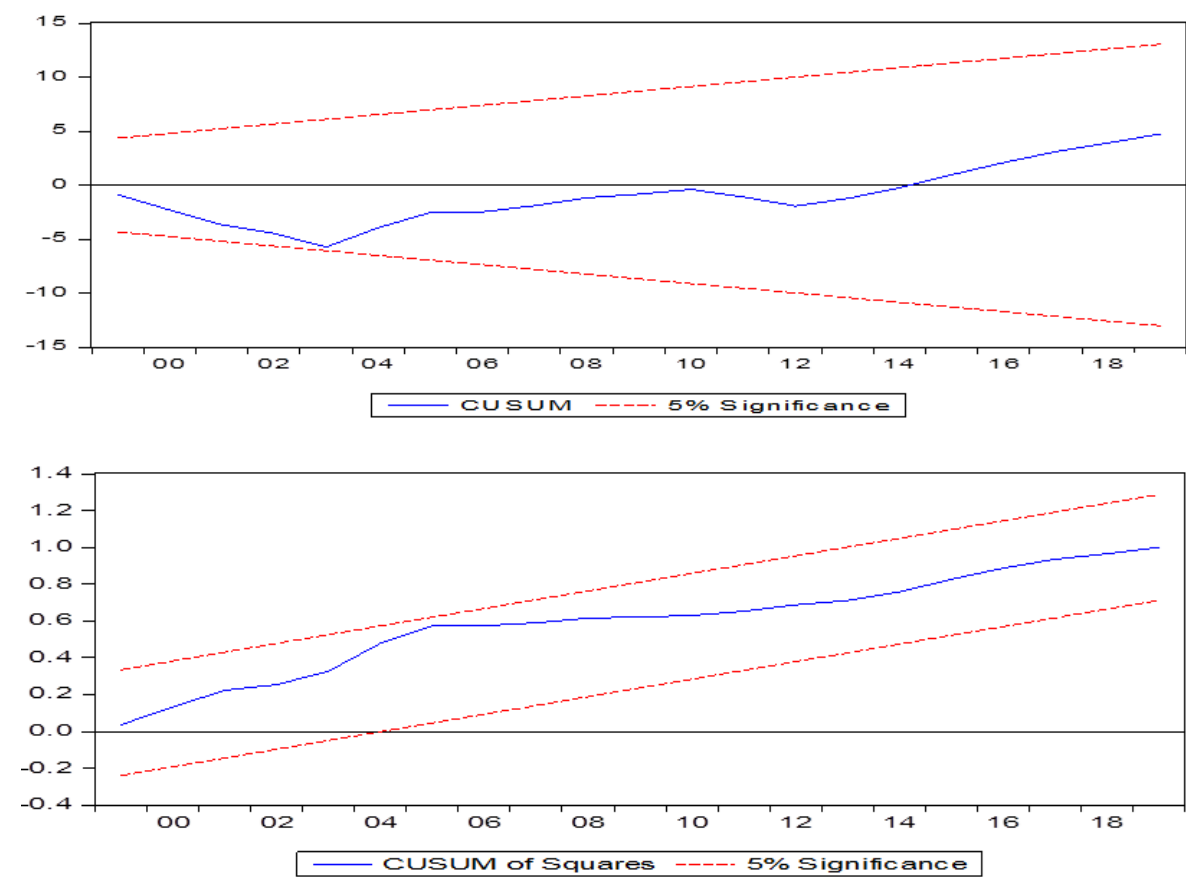
Appendices

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**



## 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

Salt stress is the most important environmental stress that adversely affects avocado morpho-physiological performance. Therefore, this study has been conducted to evaluate the response of avocado seedlings to different salinity levels. The experiment was laid out in a Randomized Complete Design (RCD) with four salt concentration levels (0, 1.3 dS/m, 2.6 dS/m, and 3.9 dS/m) on grafted avocado seedlings, with three replications. The avocado seedlings were raised from Ettinger avocado scion grafted on Guatemalan race rootstock. The results indicate that most of the morphological growth parameters, such as rootstock diameter, sucker development, and root length, were significantly ( $p < 0.01$ ) affected by salt stress level. While tap root diameter and lateral root length were not significantly ( $p > 0.05$ ) affected by salt treatment. Except for the number of suckers developed on the rootstock, rootstock and scion diameter significantly decreased as salt concentrations increased from 0 to 3.9 dS/m. Similarly, significant ( $p < 0.01$ ) variations were also observed in leaf length, bud number, leaf fresh weight and dry weight, leaf area, shoot height, taproot length, and lateral root length. These parameters were also significantly decreased with the increase in salt concentrations. Likewise, photosynthesis, transpiration, stomatal conductance, and instantaneous water use efficiency were significantly affected by salt concentration, where relatively maximum scores were obtained 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

Avocado (*Persea americana* Mill.) is native to Mexico and Central America, belonging to the family Lauraceae, and is one of the most economically important tree crops in the world (Silva and Ledesma, 2014). It has numerous advantages, particularly in terms of nutritive value (rich in monounsaturated fatty acids (MUFA), dietary fiber, essential nutrients, and phytochemicals (Fulgoni *et al.*, 2013)); it also functions as shade trees, windbreaks, and ornamen-

tals (Albertin and Nair, 2004). In the last century, it has been distributed to more than 50 countries around the world, including sub-tropical and tropical regions, with Ethiopia identified as one of the top five avocado producers in tropical Africa.

In Ethiopia, despite its long history since introduction and the presence of suitable diverse agro-ecological conditions (Wayessa and Berhanu, 2010), its distribution was still limited to a few areas of the country (Derebe *et al.*, 2023; CSA 2014). How-

ever, 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-en-set-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 are the most limiting factors in exploiting the potential of horticultural crops worldwide (Celis *et al.*, 2018). Among these, salinity, temperature, nutrition, light, oxygen availability, and metal ion concentration are the most determinant factors. Salt stress is one of the adverse environmental factors influencing physiological processes by altering the osmotic conditions in and around the plant's environment (Jouyban, 2012). High salt concentrations in the external solution of plant cells can cause various effects, which can be demonstrated in three different types: osmotic drought, toxicity due to high 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.

Tolerance to saline irrigation water is emerging as a very important quality for avocado rootstocks as it is one of the most salt-sensitive crops (Grieve *et al.*, 2012). Plants have different mechanisms to withstand saline condition. These are classified (Roy *et al.*, 2014) in to three main categories that is regulated by long-distance signals that reduce shoot growth and is triggered before shoot  $Na^+$  accumulation; ion exclusion, during which  $Na^+$  and  $Cl^-$  in the roots reduce the accumulation of toxic concentrations of  $Na^+$  and  $Cl^-$  within leaves; and, last, tissue tolerance, in which high salt concentrations are found in leaves but are compartmentalized at the cellular and intracellular levels (especially in the vacuole) (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  $CO_2$  assimilation, chlorophyll concentration, and leaf necrosis.

On the other hand, Liao *et al.* (2022) found that mild water and salt stress improved intrinsic water use efficiency (iWUE = A/gs) by (i) decreasing gs via increasing osmotic adjustment and hydraulic resistance, and (ii) declining A via increasing stomatal limitations rather than reducing photosynthetic capacity.

Furthermore, Musyimi *et al.* (2007) reported that salinity significantly affects plant overall growth, net photosynthetic rate (PN), stomatal conductance (gs), transpiration rate (E), water use efficiency (WUE) and chlorophyll (chl) concentration. As the salt concentration increases, it inhibits the growth and gas exchange of avocados.

Concurrently, Celis *et al.* (2018) also reported that rootstocks in the salt-treated soils showed extensive leaf burn. Similarly, “tip-burn” on the leaves in the fall is a sign that the tree is absorbing too much chloride, and these leaves will have to drop off during the winter. Leaves that grow to replace these often grow at the expense of flowering and fruit set, resulting in chronically low yields in some orchards.

Rootstocks vary in their ability to absorb and transport chloride and sodium. In this regard, Guatemalan rootstocks are generally intermediate in their tolerance to salinity. However, only limited research has been conducted on the comparative salinity tolerance of avocado rootstock races. Hence, identifying the performance of avocado seedlings at the early development stage under different salinity levels is highly significant in deciding on the quality of irrigation water and soil media used at the nursery. In Ethiopia, information on the response of avocado seedlings to salinity conditions is very limited. Therefore, this research is conducted to evaluate the morpho-physiological response of grafted avocado seedlings to different salinity levels at Sidama Region, Southern Ethiopia.

2 Materials and Methods

2.1 Description of the Study Area

The Study was conducted from September 2021 to October 2022 at a Dara district Tafari-Kella site in Sidama National Regional State (Figure 1); located at 350 km south of Addis Ababa at altitudes of 1850

m.a.s.l; and laid at 6°30'0"N latitude and 38°24'0"E longitude. The area receives an average of 1700 mm annual rainfall and 27°C average temperatures. The area is well characterized by a coffee fruit farming system where avocado is the dominant fruit crop in the area.

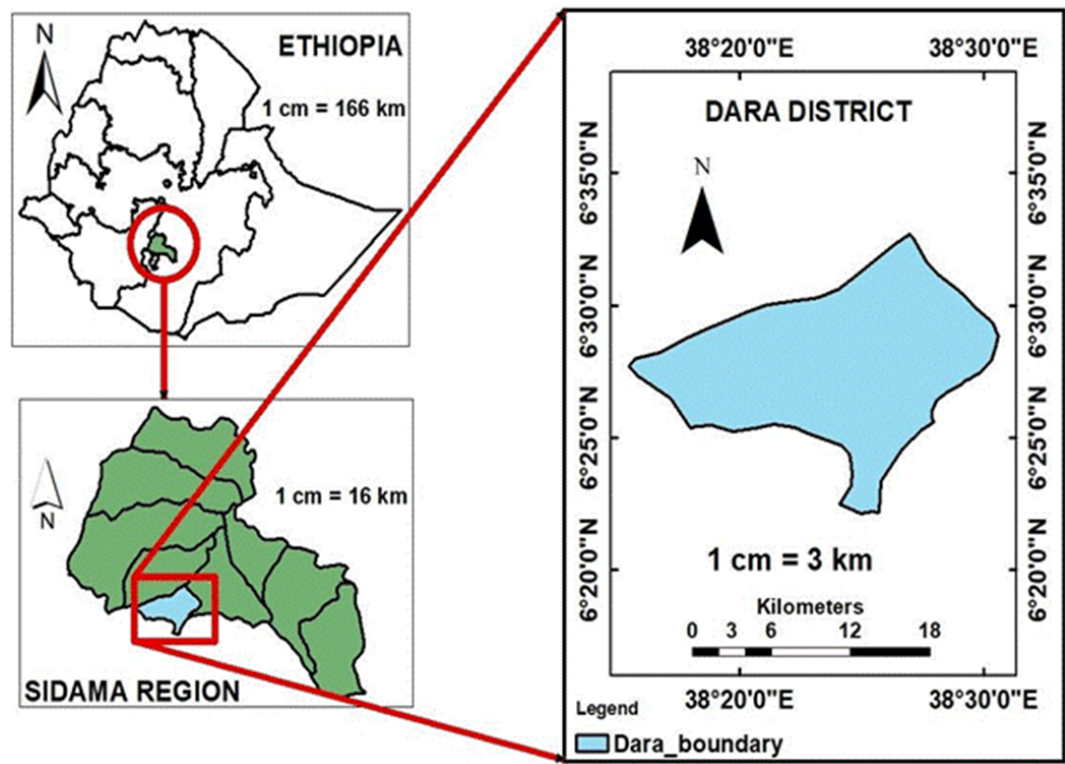


Figure 1. Map of the study area (Dara district Tafari- Kella kebele Sidama National Reginal State, Ethiopia)

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 daily maximum and minimum air temperatures for the shaded house were recorded on five selected days during the experimental period using the temperature and relative humidity data logger "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 conducted under plastic shade in 16 x 20 cm pot size that was filled with a composite soil consisting of a 3:2:1 ratio of topsoil, compost, and sand, respectively. The experiment was laid out in a Completely Randomized Design (CRD) with three replications. Each experimental unit consists of 4 pots per 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 Physico-Chemical Properties of the Experimental Soil

To determine the physicochemical properties of the soil used for the experiment, a soil sample was collected from the mixed soil prepared for planting. The composite sample was dried and ground to pass through a 0.2 mm sieve before laboratory analysis. The samples were analyzed for parameters relevant to the study, such as pH, texture class, organic carbon, total nitrogen, available phosphorus, CEC, FC, and EC (Table 1), following standard procedures at the Hawassa soil laboratory.

### 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. Data collected from the root parts included root length, tap root diameter, leaf fresh weight, stem fresh weight (g), leaf dry weight (g), root dry weight (g), leaf area (cm<sup>2</sup>), and total fresh and dry weight. All data were collected following standard procedures (Ndoro *et al.*, 2018).

### 2.5.3 Stomata anatomy

Stomata anatomy measurement was made using the protocol proposed by Xu and Zhou (2008) at 120 days after the treatment was applied. The stomata print was examined using an Automated Upright Leica Microscope DM5000 B with a 40x magnification lens fixed with a digital Leica DFC425/DFC425C image processing camera. For each sample, the following parameters were recorded: stomata number (per mm<sup>2</sup>), stomata cell number (per mm<sup>2</sup>), stomata opening (μm), and stomata length (μm).

### 2.5.4 Gas exchange and physiological parameters

Photosynthesis (A, μmol m<sup>-2</sup> s<sup>-1</sup>), transpiration rate (E), stomatal conductance (gs), and water use efficiency were estimated from three randomly selected seedlings, using the third young and fully expanded leaves. These measurements were made using a CIRAS-3 portable photosynthesis system (CIRAS-3 PP System Inc., Lincoln, NE, USA). The measurements were taken at 45 days after the actual moisture treatment was imposed on fully developed, intact leaves.

The measurements were done between 9:30 AM and 12:30 PM, with the following specifications maintained: leaf surface area of 6.25 cm<sup>2</sup>, ambient CO<sub>2</sub> concentration of 386 μmol mol<sup>-1</sup>, leaf chamber mass flow rate of 251 μmol s<sup>-1</sup>, atmospheric pressure of 840 bar, and manually fixed photosynthetic active radiation (PAR) at 600 μmol m<sup>-2</sup> s<sup>-1</sup>.

## 2.6 Statistical Analysis

All morphological and physiological data were subjected to ANOVA following the standard procedure of the General Linear Model (GLM) (Gomez and Gomez, 1984). The statistical analysis was performed using SAS statistical software version 9.0 (SAS, 2008). Mean separation was conducted at a

5% level of significance using the Least Significant Difference (LSD) test.

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

The analysis of variance revealed that rootstock diameter and the number of suckers developed on the rootstock were significantly ( $p<0.05$ ) affected by the salt stress levels, while scion diameter was not significantly affected.

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. However, no significant variation was observed in scion diameter among the different salinity levels (Table 3).

**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 <sup>-1</sup> )
Control	5.9 <sup>a</sup>	5.8	0.6 <sup>c</sup>
1.3	5.4 <sup>b</sup>	5.5	1.0 <sup>b</sup>
2.6	4.7 <sup>c</sup>	5.2	1.5 <sup>a</sup> <sub>b</sub>
3.9	4.3 <sup>c</sup>	5.0	2.0 <sup>a</sup>
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. Previous studies have reported that the highest number of leaves might be due to photosynthetic accumulation in newly grafted plants, which in turn increased the number of nodes and the absorption of moisture and nutrients by leaf primordia (Mandal *et al.*, 2012; Pampanna and Sulikeri, 1995).

**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 <sup>-1</sup> )	Leaf number (p <sup>-1</sup> )	Leave length (cm)
Control	3.04 <sup>a</sup>	5.20 <sup>a</sup> <sub>b</sub>	5.36 <sup>a</sup>
1.3	3.06 <sup>a</sup>	5.70 <sup>a</sup>	5.40 <sup>a</sup>
2.6	2.25 <sup>b</sup>	4.30 <sup>b</sup>	3.86 <sup>b</sup>
3.9	1.67 <sup>c</sup>	1.83 <sup>c</sup>	2.10 <sup>b</sup>
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≤0.05)

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

Stem diameter, plant height, scion diameter, and grafted success percentage on the rootstock were significantly ( $p<0.05$ ) affected by salt stress levels. The plant height was significantly reduced as the concentration of salinity increased.

The highest plant height (22.6 cm) was recorded from the 1.3 dS/m salt concentration, followed by 21.2 cm and 20.33 cm from the control (0 dS/m) and 2.6 dS/m salinity, respectively (Table 5). The lowest plant height (18.33 cm) was recorded from the 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). Berkessa (2020) and Bernstein *et al.* (2004) have also confirmed that avocado plants subjected to higher soil salinity levels showed a significant reduction in plant height, which might be a result of several physiological reactions, such as modification of ion balance, change in water status

(water potential) in and outside the plant cell, mineral nutrition processes, and other abnormal metabolic processes.

Reduced plant height under salinity is also associated with reactive oxygen species (ROS); as the ROS are extremely reactive and, in high amounts, noxious, leading to destructive processes and causing cellular damage (Kesawat *et al.*, 2023). Previous studies have also widely indicated that rootstocks are known to influence the salt tolerance of grafted fruit trees, including avocado (Cooper, 1951; Haas, 1950). Similarly, shoot (scion) leaf production in avocado decreases with increasing salinity (Oster and Arpaia, 1992), with differences among rootstocks influencing the extent of growth reduction under stress.

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 salinity level ds/m	Parameter			
	Stem diameter (mm)	Plant height (cm)	Scion length (cm)	Grafted success (%)
Control	21.3	21.1 <sup>a</sup> <sub>b</sub>	11.6 <sup>a</sup>	99.6 <sup>a</sup>
1.3	22.0	22.6 <sup>a</sup>	11.6 <sup>a</sup>	99.3 <sup>a</sup>
2.6	21.1	20.3 <sup>a</sup> <sub>b</sub>	8.5 <sup>b</sup>	43.3 <sup>b</sup>
3.9	20.0	18.3 <sup>b</sup>	7.9 <sup>c</sup>	25.0 <sup>c</sup>
LSD ( $p<0.05$ )	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 highest number of suckers (1.9 per plant) was

recorded in the 3.9 dS/m salt-treated plants, while the minimum sucker number was recorded at the control/0 dS/m salt concentration. 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.



This result is similar to the findings of Rana and Bhatia (2004), Bhatia and Kumar (2011), and Castro *et al.* (2009), who reported an increase in rootstock diameter under salt stress conditions.

On the other hand, Bonomelli *et al.* (2018) reported avocado tree vegetative growth stimulation under

low salinity levels in Mexican plants, which they attributed to a rise in cellular growth and an increase in cell number as a result of osmoregulation. This was also supported by Penella *et al.* (2016), who revealed that salt stress significantly stunted plant growth (-40.6% of leaf dry weight) compared to the 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 <sup>-1</sup> )	Scion diameter (mm)	Rootstock diameter (mm)
Control	1.10 <sup>b</sup>	2.17 <sup>a</sup>	20.80 <sup>a</sup> <sub>b</sub>
1.3	1.16 <sup>b</sup>	2.16 <sup>a</sup>	22.00 <sup>a</sup>
2.6	1.86 <sup>a</sup>	1.60 <sup>a</sup> <sub>b</sub>	16.00 <sup>b</sup>
3.9	1.96 <sup>a</sup>	1.45 <sup>b</sup>	15.33 <sup>c</sup>
LSD (p≤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≤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 highest root number (22.4 roots per plant) was recorded from the control treatment, while the minimum root number per plant (9.9) was recorded at 3.9 dS/m. It was also observed that the number of

roots decreased with increasing salinity levels (Table 7). A similar result was also reported by Aydinsakir *et al.* (2015).

Although root length, tap root diameter, and lateral root diameter were statistically non-significant (p>0.05), the root length increased from 3.74 to 5.48 cm (by 18.9%) as the salt concentration increased from 0 to 3.9 dS/m. On the other hand, the tap and lateral root diameters decreased from 4.9 to 3.9 mm and from 1.09 to 0.65 mm, respectively, as the 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 Salinity level (ds/m)	Parameter			
	Root number	Root length (cm)	Taproot diameter (mm)	Lateral root diameter (mm)
Control	22.44 <sup>a</sup>	3.74	4.94	1.09
1.3	16.11 <sup>b</sup>	4.15	4.20	1.00
2.6	11.33 <sup>b</sup>	4.44	4.40	0.77
3.9	9.97 <sup>b</sup>	5.48	3.90	0.65
LSD (p≤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≤0.05)

It is well-known that plant height and root length are the most important parameters for salinity because roots are in direct contact with the soil and absorb water from the soil, while the shoots supply water to the aerial parts of the plant (Jamil and Rha, 2004). Generally, inhibition of shoot and root development is the primary response to stress. Growth, morphology, anatomy, and physiology of roots are affected by salinity. Changes in water and ion uptake by the roots, production of hormonal signals that communicate information to the shoot, and changes in patterns of expression might induce changes in plant development (Bernstein *et al.* 2013).

### 3.7 Root, Leaf and Stem Fresh and Dry weight

Root fresh and dry weights did not show any statistical difference due to salinity (Table 8). However, significant variations ( $p < 0.05$ ) were observed in leaf and stem fresh and dry weights due to salt treatments.

**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 <sup>-1</sup> )	Root Dry weight (g plant <sup>-1</sup> )	Leave fresh weight (g plant <sup>-1</sup> )	Leaf dry weight (g plant <sup>-1</sup> )	Stem fresh weight (g plant <sup>-1</sup> )	Stem dry weight (g plant <sup>-1</sup> )
Control	5.48	2.76	2.86 <sup>b</sup>	1.46 <sup>b</sup>	7.24 <sup>a</sup>	3.62 <sup>a</sup>
1.3	4.44	2.57	3.87 <sup>a</sup>	1.93 <sup>a</sup>	6.69 <sup>a</sup>	3.33 <sup>a</sup> <sup>b</sup>
2.6	4.15	1.93	0.67 <sup>c</sup>	0.29 <sup>c</sup>	3.92 <sup>b</sup>	1.92 <sup>b</sup>
3.9	3.74	1.75	0.63 <sup>c</sup>	0.23 <sup>c</sup>	3.57 <sup>b</sup>	1.82 <sup>b</sup>
LSD ( $p \leq 0.05$ )	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 ( $p < 0.05$ )

Comparable results are also reported by Dolo (2018), in which he stated that salt stress causes a considerable decrease in leaf fresh and dry weights, as well as roots and stems dry weights. Similarly, Musyimi *et al.* (2007) reported that growth at high salinity concentration resulted in large reductions in fresh and dry weight production of both shoot and root. The reduction in leaf fresh weight was attributed to lower leaf number and development of smaller leaves with increased salinity of the growth medium. Bonomelli *et al.* (2018) also observed that the fresh weight of the aerial part (leaves and stems), roots, and the en-

The maximum leaf fresh (3.87 g) and dry (1.93 g) weights were recorded at 1.3 dS/m, while the minimum leaf fresh (0.63 g) and dry (0.23 g) weights were recorded at 3.9 dS/m salt concentration.

The maximum stem fresh (7.24 g) and dry (3.62 g) weights were observed at 0 dS/m, while the minimum values of 3.57 g and 1.82 g were recorded at 3.9 dS/m. These values decreased by 40% and 33%, respectively, as the salt concentration increased from 0 to 3.9 dS/m (Table 8).

The results indicate that high salinity may inhibit growth due to slowing down water uptake by the plant, which might be the reason for the decrease (Werner and Finkelstein, 1995). Salinity can rapidly inhibit stem growth and hence the capacity of water uptake and essential mineral nutrition from the soil (Neumann, 1997).

tire plant in the treatments without the stress (leaf fresh weight and stem fresh weight) were always significantly higher than treatments with saline irrigation.

### 3.8 Leaf Area, Total Fresh weight and Total dry weight

Leaf area, total fresh weight, and total dry weight were significantly ( $p < 0.05$ ) affected by salt stress. The highest leaf area (874.29 cm<sup>2</sup>) was recorded at 0 dS/m, and the minimum leaf area (159.19 cm<sup>2</sup>) was

recorded at 3.9 dS/m (Table 9). It was observed that leaf area decreased with increasing salinity levels, with a decrease of about 81.8% as the salt concentration increased from 0 to 3.9 dS/m.

The decrease in leaf area with increasing salinity levels (Aydinsakir *et al.*, 2015; Hasanuzzaman *et al.*, 2013) can be attributed to the fact that high salinity hampers cell elongation in the active growing tissue, subsequently reducing the leaf area and dry matter

assimilation in the plant.

Similarly, the highest total fresh weight (15.59 g) and dry weight (7.85 g) were recorded at the control (0 dS/m), while the minimum total leaf fresh weight (7.63 g) and dry weight (3.63 g) were recorded at the maximum salt stress level (3.9 dS/m). Concurrently, Bonomelli *et al.* (2018) also reported that cumulative leaf area, fresh weight, and dry weight increase as the salt stress level 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 <sup>2</sup> )	Total fresh weight (g plant <sup>-1</sup> )	Total dry weight (g plant <sup>-1</sup> )
Control	874.29 <sup>a</sup>	15.59 <sup>a</sup>	7.85 <sup>a</sup>
1.3	608.70 <sup>b</sup>	15.08 <sup>a</sup>	7.83 <sup>a</sup>
2.6	214.82 <sup>c</sup>	8.02 <sup>b</sup>	3.83 <sup>b</sup>
3.9	159.19 <sup>c</sup>	7.63 <sup>b</sup>	3.69 <sup>b</sup>
LSD (p≤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≤0.05)

### 3.9 Stomata number, length and width

Stomata number, stomata length, and stomata width were significantly (p<0.05) affected by salt stress levels. The maximum stomata number (22/mm<sup>2</sup>) was recorded at 0 dS/m, while the maximum stomata length (0.35 mm) and width (0.32 mm) were recorded at 1.3 dS/m, which were statistically on par with 0 dS/m.

As the salt concentration increased from 0 to 3.9 dS/m, most of the stomata parameters, including stomata number, length, and width, decreased by

25%, 23.6%, and 13.3% respectively (Table 10). Similar results were also reported by Aydinsakir *et al.* (2015), who found that stomata number decreased with increasing salinity levels.

Comparable results were also reported by Xue *et al.* (2021), who found that water and salt stress reduced stomatal length (SL), width, perimeter, and area (amax), as well as stomatal density (SD). The same trend was also reported on tomato cultivars by Guo *et al.* (2018), where salt stress substantially decreased the stomatal density, stomatal width, stomatal area, and stomatal area index.

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

Treatment Salinity level (ds/m)	Stomata number (per mm <sup>2</sup> )	Stomata length (μm)	Stomata Width (μm)
0	22.0 <sup>a</sup>	0.34 <sup>a</sup>	0.28 <sup>a</sup> <sup>b</sup>
1.3	18.6 <sup>b</sup>	0.35 <sup>a</sup>	0.32 <sup>a</sup>
2.6	15.3 <sup>c</sup>	0.24 <sup>b</sup>	0.22 <sup>b</sup>
3.9	13.6 <sup>c</sup>	0.21 <sup>c</sup>	0.21 <sup>b</sup>
LSD (p≤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≤0.05)

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

Physiological parameters such as photosynthetic rate, transpiration, gas exchange (gs), and water use efficiency were significantly ( $P<0.05$ ) influenced by salt treatments (Table 11). The transpiration rate decreased by 60% as the salt concentration increased from 0 to 3.9 dS/m, a similar result reported by Aydinsakir *et al.* (2015).

Likewise, the photosynthetic rate decreased by 51.8% as salinity levels increased from 0 to 3.9 dS/m. Hnilickova *et al.* (2021) also reported that as the concentration of NaCl reached 100 mM, they found a decrease in stomatal conductance simultaneously with an increase in CO<sub>2</sub> assimilation (A). The photosynthesis rate can drop due to stomatal closure (gas) and/or other non-stomatal limitations, like the disturbance of the photosynthetic electron chain and inhibition of Calvin cycle enzymes (Chaves *et al.*, 2009). A drop in gas exchange can prevent excess water loss by transpiration, whereas proper regulation of the photosynthetic process can minimize the generation of ROS in PS2 and in the reducing side of the PS1 (Asada, 1999).

Similarly, Musyimi *et al.* (2007) reported that the

decline in net photosynthesis with increasing salinity is associated with a similar reduction in gs in salt-treated plants. Reduction in photosynthesis is directly related to stomatal conductance, though non-stomatal factors are also associated with lower photosynthetic capacity in salt-treated plants (Ashraf, 2002; Netondo *et al.*, 2004). Schaffer and Whiley (2003) have indicated that stomatal conductance is a more reliable early indicator of salt stress in avocado than measurements of leaf water content, leaf water potential, or other growth variables.

Redondo-Gómez *et al.* (2007) found that the net photosynthetic rate (A) declined significantly with increasing external salinity after 6 days of treatment. Guo *et al.* (2018) reported that NaCl stress resulted in marginal declines in the net photosynthetic rates (Pn), stomatal conductance (gs), and transpiration rates (Tr) of avocado cultivars they used in their study. Similar observations were also reported in mature avocado trees irrigated with an EC = 1.5 dS/m salinity level (Acosta-Rangel *et al.*, 2019), where the avocado leaves visibly damaged by the salinity (named as partially burned leaves) experienced photoinhibition and reduction of photosynthetic rate and water-use efficiency, suggesting that the poor performance in carbon assimilation contributed to reductions in yield and increases in 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 <sup>a</sup>	3.05 <sup>a</sup>	116.6	2.84 <sup>a</sup>
1.3	4.63 <sup>ab</sup>	2.72 <sup>ab</sup>	110.6	2.75 <sup>a</sup>
2.6	3.96 <sup>ab</sup>	2.26 <sup>ab</sup>	71.6	2.35 <sup>ab</sup>
3.9	2.60 <sup>b</sup>	1.29 <sup>b</sup>	57.6	1.48 <sup>b</sup>
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. However, these

crops are exposed to various biotic and abiotic stress conditions. Among abiotic stresses, salinity is one of the environmental stresses that adversely affects growth, physiology, and yielding potential. The avo-

cado plant is very sensitive to such stress prevalent in the subtropics. However, there are limited studies that have focused on the performance of avocado seedlings under such stress conditions.

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. Except for the number of suckers on the root part, which shows an increasing trend, as the salt concentration increased from 0 to 3.9 dS/m, most of the vegetative growth parameters decreased with increasing salt concentration. These parameters include the number of buds, leaf number, leaf length, stem diameter, plant height, scion length, and scion and rootstock diameter.

Growth at high salinity resulted in large reductions in the fresh and dry weight production of both the shoot and root parts of avocado seedlings. The observed fresh and dry weight of the aerial part (leaves and stems) and underground root parts were significantly higher in the treatments without the stress compared to the treatments with saline conditions.

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<sup>-1</sup> for CEC, 0.97% to 0.47% for SOC, 1.76 to 1.40 g cm<sup>-3</sup> for bulk density, 30.31 to 37.21% for porosity, 30.25 to 34.55 μS cm<sup>-1</sup> for EC, 2.56 to 0.26 cmol Kg<sup>-1</sup> 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 (Achaluet *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 (Achaluet *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  $09^{\circ}25'33''$  and  $09^{\circ}33'16''$  N and longitude of  $35^{\circ}24'32''$  and  $35^{\circ}36'28''$  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 ( $\text{NaOH}$ ), 10  $N$ , concentrated  $\text{H}_2\text{SO}_4$ , and saturated boric acid solution ( $\text{H}_3\text{BO}_3$ ) for nitrogen determination using the Kjeldahl procedure. Ammonium acetate Solution (1  $\text{NNH}_4\text{OAc}$ ), for extraction of  $\text{Ca}$ ,  $\text{Mg}$ , and  $\text{K}$ ; 0.005  $M$  EDTA (Ethylene-diamine tetra acetic acid), 6  $N$  hydrochloric acid ( $\text{HCl}$ ), 0.1  $M$  TEA (Triethanolamine), 0.1  $\text{M}\text{CaCl}_2$  (calcium chloride) for extraction of micronutrient cations ( $\text{Fe}$ ,  $\text{Zn}$ ,  $\text{Mn}$ ,  $\text{Cu}$ ) and  $\text{HNO}_3 - \text{HClO}_4$  di-acid mixture for digestion of samples for micronutrients determination; 2 %  $\text{NaCN}$  (Sodium cyanide) to prevent interference of  $\text{Fe}$ ,  $\text{Zn}$ ,  $\text{Mn}$ ,  $\text{Cu}$  while measuring  $\text{Ca}$  and  $\text{Mg}$  with atomic absorption spectrophotometer (AAS). Hydrochloric acid ( $\text{HCl}$ ), 0.05  $N$  for boron ( $\text{B}$ ) determination; 0.4  $\text{NK}_2\text{Cr}_2\text{O}_7$  solution (2:1)  $\text{H}_2\text{SO}_4$ :  $\text{H}_3\text{PO}_4$  mixture, mercury (II) oxide ( $\text{HgO}$ ), 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  $\text{Mg}$ ,  $\text{Ca}$ ,  $\text{Zn}$ ,  $\text{Fe}$ ,  $\text{Cu}$ ,  $\text{Mn}$ , and  $\text{Mo}$  were determined by AAS. Flame atomic photometer (FAAS) was used for the determination of  $\text{K}$ ; Uv-Vis was used spectrophotometer for the determination of  $\text{B}$ ,  $\text{P}$ .

### 2.4 Physicochemical analysis of the soils

Standard procedures were followed to measure some important physical and chemical characteristics of the soils. Thus, the  $\text{pH}$  values of the soils were determined by using combined-glass electrodes in  $\text{H}_2\text{O}$  and 0.01  $M$   $\text{CaCl}_2$  suspension before and after lime application. Neutral 1  $N$  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 0.02  $M$   $\text{NaOH}$  (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  $\text{H}_2\text{O}$ ) by following the methods described by Rowell (Van Reeuwijk,

1992). The cations such as  $\text{Na}$  and  $\text{K}$  were determined using FAAS,  $\text{Ca}$ ,  $\text{Mg}$ ,  $\text{Cu}$ ,  $\text{Fe}$ ,  $\text{Mn}$ , and  $\text{Zn}$  were analyzed using AAS after being extracted using 1  $N$  Ammonium acetate ( $\text{NH}_4\text{OAc}$  at  $\text{pH}$  7). The available form of  $\text{P}$  was determined following Bray I (Bray and Kurtz, 1945), Mehlich 3- $\text{P}$  (Mehlich, 1984), Olsen method (Olsen and Sommers, 1982), and  $\text{CaCl}_2$  extraction methods depending on soil  $\text{pH}$  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  $\text{pH}$  values of 5.4, 6.0, and 7.4. This method was chosen for its relatively simple laboratory procedures. These target  $\text{pH}$  values are within the optimum  $\text{pH}$  ranges for the growth of many crops, and this is why they were chosen as target  $\text{pH}$  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 ( $\text{kg ha}^{-1}$ ); LRF is the lime requirement factor ( $\text{kg lime ha}^{-1}$ ) to lower the exchangeable acidity by 1  $\text{cmol}$ . The accepted value of LRF is 3000  $\text{kg lime ha}^{-1} \text{cmol}^{-1}$  for most Ethiopian soils (Farina 1991; Sertsu & Bekele, 2000); Ex. Ac = exchangeable acidity ( $[\text{Al}^{3+}] + [\text{H}^+]$ ); 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 ( $\text{CaCO}_3$ ) powder was used as liming material. For each target  $\text{pH}$  value, the quantities of  $\text{CaCO}_3 \text{ ha}^{-1}$  (in  $\text{mmolc}$ ) added were computed, and the field level was expressed in  $\text{kg}$  of equivalent  $\text{CaCO}_3 \text{ ha}^{-1}$ . Then, from each sample, 4  $\text{kg}$  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 (Houbaet *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 ( $KgCaCO_3 ha^{-1}$ )

Soils	<i>pH</i> of Soils	Target <i>pH</i> 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 ( $\text{kg CaCO}_3 \text{ ha}^{-1}$ ) 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  $\text{kg CaCO}_3 \text{ ha}^{-1}$ , 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  $\text{cmolc kg}^{-1}$ ) 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  $\text{cmol kg}^{-1}$ ), SOC (0.97 to 0.47%), EC (30.25 to 34.55  $\mu\text{S cm}^{-1}$ ), EA (2.56 to 0.26  $\text{cmol kg}^{-1}$ ) and TN (0.02 to 0.08%), AP (1.76 to 6.79  $\text{mg kg}^{-1}$ ), 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 TN 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 ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) in the liming materials with phosphorus fixing cations ( $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ ) 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 <sub>2</sub> O)	Bd (g cm <sup>-3</sup> )	Porosity (%)	MC (%)	CEC (CmolKg <sup>-1</sup> )	EC (μS cm <sup>-1</sup> )	EA (Cmol Kg <sup>-1</sup> )	SOC (%)	TN (%)	TP (mg Kg <sup>-1</sup> )	C:N (%)	Textural Class
Physicochemical properties of the six sample soils before liming												
AA	4.72 <sup>f</sup>	1.45 <sup>c</sup>	37.22 <sup>g</sup>	21.12 <sup>g</sup>	28.14 <sup>f</sup>	32.43 <sup>f</sup>	2.45 <sup>c</sup>	0.89 <sup>b</sup>	0.06 <sup>d</sup>	1.67 <sup>i</sup>	14.83 <sup>a</sup>	Silty-Clay
BD	4.54 <sup>g</sup>	1.76 <sup>a</sup>	30.31 <sup>h</sup>	24.88 <sup>e</sup>	36.59 <sup>b</sup>	30.25 <sup>g</sup>	2.56 <sup>b</sup>	0.97 <sup>a</sup>	0.02 <sup>e</sup>	1.76 <sup>h</sup>	12.13 <sup>d</sup>	Clay
KB	4.46 <sup>g</sup>	1.47 <sup>c</sup>	40.94 <sup>f</sup>	28.23 <sup>d</sup>	27.24 <sup>f</sup>	28.41 <sup>i</sup>	2.98 <sup>a</sup>	0.99 <sup>a</sup>	0.09 <sup>a</sup>	1.87 <sup>g</sup>	11.00 <sup>e</sup>	Clay-loam
KG	5.21 <sup>d</sup>	1.66 <sup>b</sup>	47.16 <sup>b</sup>	30.21 <sup>c</sup>	34.71 <sup>c</sup>	37.34 <sup>b</sup>	2.14 <sup>c</sup>	0.86 <sup>b</sup>	0.07 <sup>c</sup>	1.93 <sup>f</sup>	12.29 <sup>c</sup>	Silty-Clay
NG	4.97 <sup>e</sup>	1.68 <sup>b</sup>	50.00 <sup>a</sup>	27.36 <sup>d</sup>	36.32 <sup>b</sup>	33.35 <sup>e</sup>	2.28 <sup>b</sup>	0.88 <sup>b</sup>	0.07 <sup>c</sup>	1.39 <sup>k</sup>	12.57 <sup>b</sup>	Silty-Clay
WG	5.14 <sup>d</sup>	1.48 <sup>c</sup>	39.80 <sup>d</sup>	30.62 <sup>c</sup>	29.37 <sup>d</sup>	35.31 <sup>c</sup>	2.12 <sup>c</sup>	0.98 <sup>a</sup>	0.08 <sup>b</sup>	1.54 <sup>j</sup>	12.25 <sup>c</sup>	Clay-loam
Physicochemical properties of the six sample soils after liming												
AA	6.80 <sup>b</sup>	1.31 <sup>e</sup>	43.39 <sup>c</sup>	23.22 <sup>f</sup>	30.34 <sup>e</sup>	34.46 <sup>d</sup>	0.65 <sup>f</sup>	0.28 <sup>d</sup>	0.02 <sup>g</sup>	2.68 <sup>d</sup>	14.82 <sup>a</sup>	Silty-Clay
BD	6.46 <sup>c</sup>	1.40 <sup>d</sup>	37.21 <sup>g</sup>	25.28 <sup>e</sup>	37.19 <sup>a</sup>	34.55 <sup>d</sup>	0.26 <sup>g</sup>	0.47 <sup>c</sup>	0.08 <sup>b</sup>	6.79 <sup>a</sup>	12.11 <sup>d</sup>	Clay
KB	6.42 <sup>c</sup>	1.23 <sup>d</sup>	43.00 <sup>c</sup>	30.43 <sup>c</sup>	29.44 <sup>f</sup>	29.49 <sup>h</sup>	1.18 <sup>d</sup>	0.45 <sup>c</sup>	0.06 <sup>d</sup>	4.88 <sup>b</sup>	11.02 <sup>e</sup>	Clay-loam
KG	7.12 <sup>a</sup>	1.43 <sup>d</sup>	47.34 <sup>b</sup>	33.26 <sup>b</sup>	36.72 <sup>b</sup>	39.24 <sup>a</sup>	0.64 <sup>f</sup>	0.27 <sup>d</sup>	0.03 <sup>f</sup>	3.79 <sup>c</sup>	12.22 <sup>c</sup>	Silty-Clay
NG	6.88 <sup>b</sup>	1.43 <sup>d</sup>	51.28 <sup>a</sup>	30.38 <sup>c</sup>	37.38 <sup>a</sup>	35.35 <sup>c</sup>	0.98 <sup>e</sup>	0.26 <sup>d</sup>	0.03 <sup>f</sup>	1.34 <sup>k</sup>	12.52 <sup>b</sup>	Silty-Clay
WG	7.22 <sup>a</sup>	1.30 <sup>e</sup>	42.35 <sup>e</sup>	34.78 <sup>a</sup>	30.39 <sup>d</sup>	37.35 <sup>b</sup>	0.65 <sup>f</sup>	0.48 <sup>c</sup>	0.04 <sup>e</sup>	2.14 <sup>e</sup>	12.21 <sup>c</sup>	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 <sup>2</sup>	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 = Cation exchange capacity; EC = Electrical conductivity; EA = Exchangeable acidity; OC = Organic carbon;

TN = Total nitrogen; LR = Lime requirement; AP = 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, TN, and AP 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

	<i>pH</i>	Bd	Porosity	CEC	EC	EA	SOM	TN	C:N	AP
<i>pH</i>	1									
Bd	0.05	1								
Porosity	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			
TN	-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	
AP	0.68**	0.14*	0.13*	0.48**	0.16*	-0.69**	0.66**	0.43**	0.38**	1

Bd= Bulk density; Porosity= porosity; CEC= Cation exchange capacity; EC= Electric conductivity; EA= Exchangeable acidity; SOM= Soil organic matter; TN= Total nitrogen; C:N= Carbon to nitrogen ratio; AP= 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 physicochem-

ical 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	$K^+$	$Ca^{2+}$	$Mg^{2+}$	$Fe^{3+}$	$Mn^{2+}$	$Zn^{2+}$	$Cu^+$	<i>Mo</i>	$Al^{3+}$ mgL <sup>-1</sup>
Exchangeable cations in the six different soils before liming									
AA	1.21 <sup>g</sup>	7.42 <sup>f</sup>	2.44 <sup>j</sup>	901.01 <sup>e</sup>	112.64 <sup>e</sup>	4.75 <sup>c</sup>	3.59 <sup>h</sup>	17.92 <sup>e</sup>	510.42 <sup>f</sup>
BD	1.07 <sup>g</sup>	5.93 <sup>g</sup>	3.33 <sup>h</sup>	921.87 <sup>d</sup>	113.58 <sup>e</sup>	4.63 <sup>d</sup>	2.96 <sup>i</sup>	12.09 <sup>f</sup>	641.01 <sup>c</sup>
KB	1.16 <sup>g</sup>	2.58 <sup>j</sup>	1.86 <sup>k</sup>	1120.11 <sup>a</sup>	122.64 <sup>c</sup>	3.44 <sup>g</sup>	4.89 <sup>f</sup>	20.05 <sup>d</sup>	621.74 <sup>d</sup>
KG	2.59 <sup>f</sup>	3.77 <sup>i</sup>	2.48 <sup>i</sup>	992.65 <sup>c</sup>	137.61 <sup>a</sup>	3.76 <sup>e</sup>	5.18 <sup>e</sup>	26.79 <sup>c</sup>	531.97 <sup>e</sup>
NG	3.82 <sup>e</sup>	5.65 <sup>g</sup>	4.02 <sup>g</sup>	1102.25 <sup>b</sup>	125.51 <sup>b</sup>	6.92 <sup>a</sup>	7.92 <sup>a</sup>	32.98 <sup>b</sup>	764.15 <sup>a</sup>
WG	2.76 <sup>f</sup>	4.47 <sup>h</sup>	1.86 <sup>k</sup>	1121.06 <sup>a</sup>	118.57 <sup>d</sup>	6.87 <sup>b</sup>	7.12 <sup>b</sup>	33.24 <sup>a</sup>	745.83 <sup>b</sup>
Exchangeable cations in the six different soils after liming									
AA	4.39 <sup>c</sup>	36.84 <sup>e</sup>	66.08 <sup>d</sup>	34.29 <sup>j</sup>	27.65 <sup>g</sup>	2.14 <sup>i</sup>	5.28 <sup>e</sup>	1.76 <sup>j</sup>	27.61 <sup>k</sup>
BD	4.05 <sup>d</sup>	36.93 <sup>e</sup>	58.35 <sup>f</sup>	33.57 <sup>k</sup>	27.75 <sup>f</sup>	2.36 <sup>h</sup>	4.11 <sup>g</sup>	1.26 <sup>k</sup>	27.86 <sup>k</sup>
KB	4.74 <sup>b</sup>	39.38 <sup>d</sup>	59.82 <sup>e</sup>	47.99 <sup>f</sup>	25.51 <sup>h</sup>	3.78 <sup>e</sup>	6.92 <sup>c</sup>	3.93 <sup>g</sup>	37.91 <sup>j</sup>
KG	5.68 <sup>a</sup>	45.43 <sup>c</sup>	76.84 <sup>c</sup>	35.02 <sup>i</sup>	23.52 <sup>j</sup>	3.52 <sup>g</sup>	7.18 <sup>b</sup>	2.01 <sup>h</sup>	42.01 <sup>h</sup>
NG	4.77 <sup>b</sup>	50.29 <sup>a</sup>	98.6 <sup>a</sup>	46.85 <sup>g</sup>	27.78 <sup>f</sup>	2.42 <sup>h</sup>	7.79 <sup>a</sup>	1.86 <sup>i</sup>	48.06 <sup>g</sup>
WG	5.66 <sup>a</sup>	48.96 <sup>b</sup>	91.4 <sup>b</sup>	44.21 <sup>h</sup>	25.35 <sup>i</sup>	3.46 <sup>g</sup>	6.32 <sup>d</sup>	1.17 <sup>l</sup>	41.94 <sup>i</sup>
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, particularly for the least developed countries, although the challenge remains tough. The research was designed to analyze the food security status of households and its determinant factors in the Majang Zone. A multistage sampling was employed to select the 320 households. The study employed a mixed design that uses questionnaires, focus group discussions (FGDs), and key informant interviews (KIIs) to generate data. The data were analyzed using descriptive and binary logistic regression. The findings indicated that nearly 53% and 47% of the households were food secure and insecure, respectively. 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 ( $p < 0.10$ ) significantly and positively determine the household food security status, whereas age ( $p < 0.05$ ) and pesticide use ( $p < 0.05$ ) have negative relationships. A unit increase in the above factors is expected to improve food security by a fold of 0.1014, 2.138, 1.489, 2.237, 0.9674, 0.0001, 2.469, and 0.7226, 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

Ensuring food and nutritional security is the human and constitutional right of all citizens, though it remains a challenge, particularly in low-income countries. Food security is achieved 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). Globally, despite efforts to address food security crises, nearly 690 million people have been hungry, more than 250 million

of whom live in Africa (FAO *et al.*, 2021). It was suggested that the COVID-19 pandemic might have affected 83–132 million people worldwide by 2020. In Ethiopia, the number of poor and food-insecure people has remained very high, with an estimated 25 million people living at or below the threshold of survival (Diriba, 2020). Of these, 8.5 million were estimated to be severely food insecure in early 2020 (FAO *et al.*, 2021; IPC, 2020). According to Luminița (2016), nearly 10.2 million people were in emergency food security settings. Approximately 52% and 36% of rural and urban populations, respectively,

consume less than the minimum recommended daily intake of 2100 kcal/person/day (Debebe, 2018). In response, the government tends to augment the food gap with food aid, where more than eight million people participate in PSNP transfers (Gilligan *et al.*, 2023).

In Ethiopia, natural, social, physical, economic, and political factors are the main causes of food insecurity and unsustainable food systems (Endalew *et al.*, 2015; World Bank, 2010; Regassa, 2011; FAO, 2010; Andersson *et al.*, 2011; Eneyew and Bekele, 2012). Keller (2009) indicated that policy and program implementation gaps are another problem. For instance, drought, flooding, ecosystems, and biodiversity damage are claimed to be the driving factors (Simane *et al.*, 2016). The FAO (2017) reported that famine and rain irregularities or seasonal disparities were the main causes of food insecurity in Ethiopia. Frequent floods and droughts, such as the latest El Niño damage in 2015 and 2016, have occurred throughout the country's history and have caused enormous losses in life and assets (FAO *et al.*, 2017; UNDP *et al.*, 2010; World Bank, 2017). Ethiopia has experienced more than 15 drought events over the last 50 years (Kasie, 2017). It has also been claimed that the country is structurally food insecure where food access has been impeded due to infrastructural, economic, and political instabilities, although food may be available at some point (Vedeld *et al.*, 2007).

Natural resources misuse, drought, poor off-farm employment, diseases, poor access to the market and credit, poor access to drinking water and sanitation, policy gaps, and price inflation of food items were reported causes of food insecurity in the study area (Mathewos & Bewuketu, 2018; Guyalo *et al.*, 2022; Girma & Muluneh, 2021). Despite the challenges in ensuring food security, little research has been conducted to address the core issues that trigger food insecurity. Most of the available evidence on food security comes from routine government documents

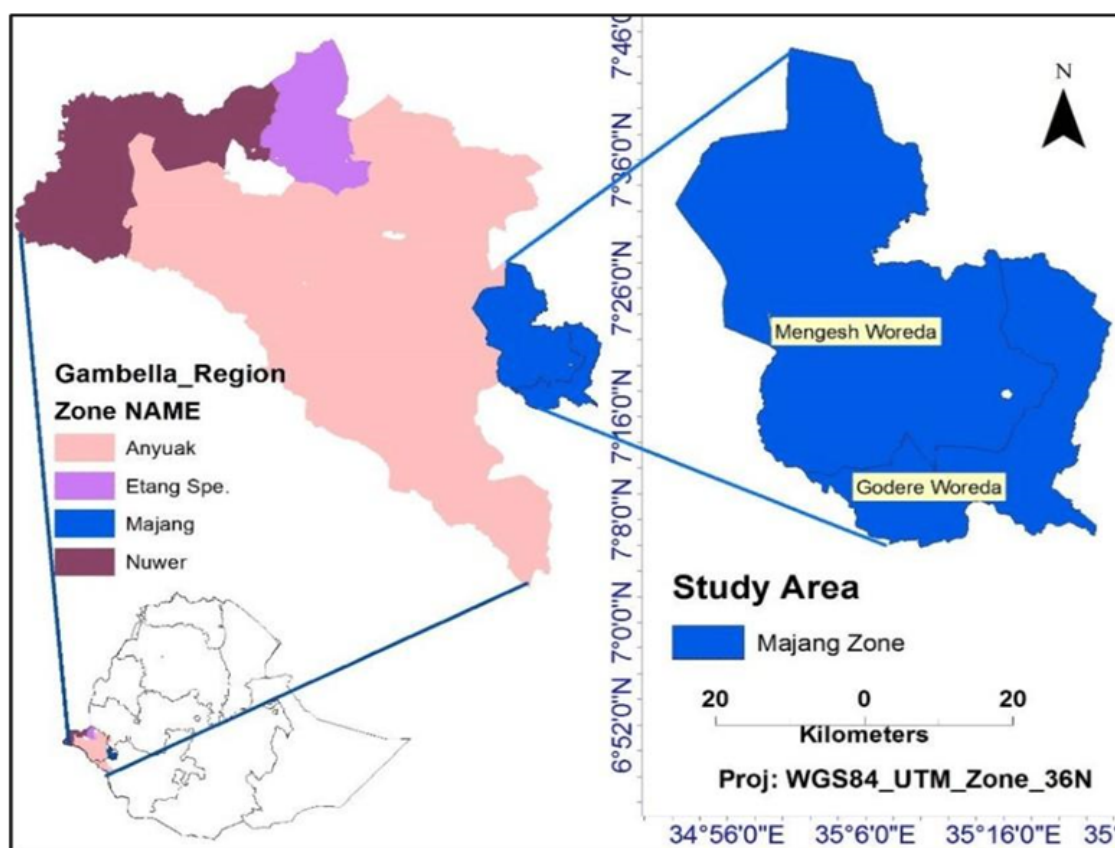
and emergency assessment reports. This gap has resulted in duplicate efforts, inappropriate prioritization, and irregular planning and implementation of food security interventions. Furthermore, the livelihoods of many households in the area depend on forest and forest-related non-timber products; however, these issues are seldom addressed in scientific research. To address these issues, this study investigated the influence of food security determinants on rural households' food security status in the Majang zone.

## 2 Materials and Methods

### 2.1 Description of the Study Area

This study was conducted in the Majang zone of the Gambella Region of Ethiopia. The zone is located at latitude 7° 4' 2.41" N to 7° 46' 47.79" N and longitude 34° 36' 30.54" E to 35° 38' 48.00" E. The Zone has two districts, Godere and Mangeshi, which constitute the total study area (Figure 1).

The climate of the study area was hot and humid. Although there were no meteorological stations in the study area, the mean annual rainfall was estimated to be approximately 2100 mm. The mean temperature ranged between 20 and 33°C. The area is characterized by a flat to gentle slope, with rocky steep and deep valleys along major streams and hills (Guyalo *et al.*, 2022). The total land cover of the zone is 2252.79 km<sup>2</sup> (Central Statistical Agency, 2007). According to the CSA projected population census for the year 2022, the zone has a total population of 89,033, of which 46,119 are male and 42,914 are female. The estimated population density of the zone was 39.5 people per square kilometer. Godere and Mangeshi Districts have 12 and 14 villages, respectively, with projected populations of 61,079 and 27,954, respectively. Approximately 88% of the population is rural, with an average of 5.3 individuals per household and a large proportion under 20 years old (more than 60%).



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

## 2.2 Study Design and Data Collection Tools

The present study employed an embedded design that aimed to collect qualitative and quantitative data simultaneously or sequentially, but to ensure that the quantitative results were consistent with the qualitative results (Creswell, 2009). Degefa (2006) affirmed the mixed research design as the foundation of food security research because it allows for the analysis of food security in multiple dimensions. This study used household-based cross-sectional data. Hence, the data collection involved quantitative and qualitative methods from primary and secondary sources. The data gathering tools include structured survey questionnaires, focus group discussions (FGDs), key informant interviews (KIIs), and desk reviews. Food consumption data were collected using the standard survey module of the food consumption score (FCS) developed by the World Food Programme (WFP, 2008).

Primary data were collected using structured household survey questionnaires, FGDs, and KIIs from household respondents, rural extension workers, gov-

ernment and non-governmental organization (NGO) experts, and officials working on food security. Secondary data were collected from published articles, periodic reports, and assessment documents from government and NGO bureaus and offices. 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 adopted to select the study households. First, two districts, Mangeshi and Godere, were purposely selected because the zone has only two districts, and these districts share similar livelihoods and administrative boundaries. Second, a systematic random sampling technique was used to select 10 villages - four in Godere and six in Mangeshi - out of the 32 villages based on the assumption that a large sampling ratio (approximately 30%) was appropriate for small

populations (<1,000). The sample villages were included based on prior discussions and assumptions of subsistence agriculture, Majang community dominance, and attachment to forest-based livelihoods. To determine the sample size for each village, the 2022 projected population (households) of each village was used to calculate the respondent households from each village, based on the total household proportion share. The total population and households of the 10 villages are projected to be 15,826 and 3,557, respectively. Finally, household respondents were randomly sampled by applying the probability proportional to size technique to large populations, as described by Cochran (1977).

$$n_0 = \frac{Z^2 pq}{e^2} \quad (1)$$

where  $n_0$  is the sample size and  $Z^2$  is the abscissa of the normal curve that cuts off an area  $\alpha$  at the tails ( $1 - \alpha$  equals the desired confidence level). For this research, a 95% confidence interval was assumed, and the Z table value was 1.96;  $e$  is the desired level of precision;  $p$  (0.6) is the estimated proportion of an attribute or all forms of food-insecure households that are present in the zone's population; and  $q$  is  $1 - p$ , as highlighted in the reports of DRMFSS (2015). Based on the above formula, the sample size was 369 households.

Considering (Cochran, 1977) sample size correction for sample sizes exceeding 5% of the population, the final sample size is determined as follows:

$$n_1 = \frac{n_0}{1 + \frac{n_0}{N}} \quad (2)$$

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. Accordingly, the final sample size was  $[369/1+(369/3557)]=334$ . Owing to incomplete information in some household data, few were omitted, and 320 sample households composed the sampling unit for the final analysis.

## 2.4 Data Analysis

The quantitative data on the factors determining food security were analyzed using both descriptive and bivariate econometric analysis methods with STATA version 13. Qualitative data were analyzed by extracting, grouping, and synthesizing the information

from the responses to substantiate and supplement the results of the quantitative analysis.

The Food Consumption Score (FCS) standard module was used to collect data, following the procedures given in the WFP (2008) guidelines. The descriptive statistics included the mean, frequency, standard deviation, and percentage, which were used to determine the level of influence of the determinant factors of household food security and to provide insight into different socioeconomic characteristics.

Logistic regression (binary logit) was used to investigate the correlates of household food security. The binary logit econometric model was specified based on the variables under study and in reference to multiple similar research articles, including those by Moroda *et al.* (2018) and Hailu *et al.* (2018). There is no compelling reason to choose the logit over the probit model unless its comparative mathematical simplicity. The functional form of the logit model is specified in the following mathematical presentation:

Logit model:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \varepsilon$$

where:

$p$  is the probability of being food secure

$\beta_0$  is the intercept

$\beta_1, \beta_2, \dots, \beta_n$  are the coefficients of the explanatory variables  $X_1, X_2, \dots, X_n$

$\varepsilon$  is the error term.

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

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

$$P_i = \frac{1}{1 + e^{Z_i}} = \frac{e^{Z_i}}{1 + e^{Z_i}} \quad (4)$$

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  $\beta_0$  and  $\beta_j$  are the parameters to be estimated. If  $P_i$  is the probability that a household is food secure, as given in equation 2, the probability of food insecurity is expressed as follows:

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

The odds ratio is calculated with equation 6:

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

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

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

Where  $\beta_0$  is a constant, and  $\beta_i$ , where  $i = 1, 2, \dots, j$ , are the coefficients of the variables to be estimated.  $X_i$  is a vector of the explanatory variables.

The Food Consumption Score (FCS) is calculated from the types of foods and the frequencies with which they are consumed during a seven-day period. The FCS is measured on a continuous scale that is subsequently subjected to categorization of households into predetermined thresholds. Hence, standard statistics, such as the mean and variance, can be calculated, and trends of means over time and across categories can be determined. Frequencies and cross-tabulations can be determined for the food consumption groups.

Procedurally, the food items were grouped into eight standard food groups with a maximum value of 7 days/week. Next, the consumption frequency of each food group was multiplied by an assigned weight, based on its nutrient content. These values were subsequently summed to obtain the FCS.

The typical thresholds used by WFP (2008) are 0-21 (poor), 21.5-35 (borderline), and >35 (acceptable). However, for populations that have a high frequency of oil and sugar consumption (daily or almost daily), alternate cut-offs are proposed as 0-28 (poor), 28.5-42 (borderline), and >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

It is well known that most studies use two approaches to measure food security: the household food balance sheet and another method for assessing food consumption (food calorie intake in kilocalories/day/AE) (Feleke *et al.*, 2013). Furthermore, the WFP (2008) claimed that the Food Consumption Score (FCS) is a prominent food consumption measurement tool and proxy for food security because it captures both caloric intake and diet quality at the household level. Hence, this study specifies households' food security status as the outcome variable determined by the FCS.

Procedurally, the household food consumption score is compared with predetermined cut-offs to classify the households into three food consumption groups:

- 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, to estimate the determinants of the probability that the households under study would be food insecure, they were categorized into food secure and food insecure households by taking 42 as the FCS threshold. Therefore, all households that scored an FCS of 42 or less were categorized as food insecure, and those with an FCS greater than 42 were considered to be food secure. Thus, the dependent variable, food security status, is assigned a value of 1 (>42) if food security is considered to exist, and 0 ( $\leq 42$ ) otherwise.



The proportion of the population with poor and borderline food security reflects the prevalence of food insecurity, and an acceptable proportion indicates food security (WFP, 2010).

### **Independent variables**

**Age of household head (AGE):** This is a continuous variable measured in years. This study assumes younger households maintain food security better.

**Sex of household head (SEXH):** This is a dummy variable that influences households' state of food security. It is hypothesized that male-headed households are more likely to be food-secure.

**Family size of households (FSZH):** Family size refers to the total number of household members; hence, this variable is continuous. Given that they are of productive age, a large family is hypothesized to be involved in diverse productive activities on both farms and off-farm farms to support the fulfilment of 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. It is hypothesized that the higher the dependency ratio, the less the household becomes 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. It is hypothesized that house-

holds with large amounts of fertile cultivated land have a greater probability of being food secure than small landholders.

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

**Oxen ploughing of farmland (OXPL):** This variable enables farmers to gain the advantages of time, labor, and waste of food energy. Hypothetically, in this study, this variable has a positive correlation with household food security.

**Agricultural extension service (AEXS):** Technical visit experts increased the probability of being food secure. The variable is a dummy variable.

**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):** An important dummy variable that takes a value of 1 for yes and 0 otherwise, which supports the food security attainment endeavor of households.

**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 takes the value of one if the household takes credit and zero otherwise. Thus, a household with access to credit is more likely to be food-secure.

**Cooperative Membership (COOP):** This is a dummy variable that takes a value of 1 for a yes response and 0 otherwise. This variable is positively correlated with food security.

**Off-farm income (OFINC):** Income is measured in terms of birr and is therefore a continuous variable. Hence, it is hypothesized that the availability of off-farm income is positively associated with household food security.

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

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 mean age of the study households was approximately 40 years, with a minimum and maximum age of 18 and 75 years, 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.

The overall descriptive statistics provided evidence of the prevalence of high levels of food insecurity in the study area, and multiple factors contributed to this difference. The results revealed that 53.12% of households were food secure and 46.88% were food insecure, as determined by their food consumption measures. The mean percentage of dependent household members was greater (108%) in the study area, with the highest percentage reaching 250%.

### 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 ma-

**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 descriptive analysis results further explained that of the total respondent households, approximately

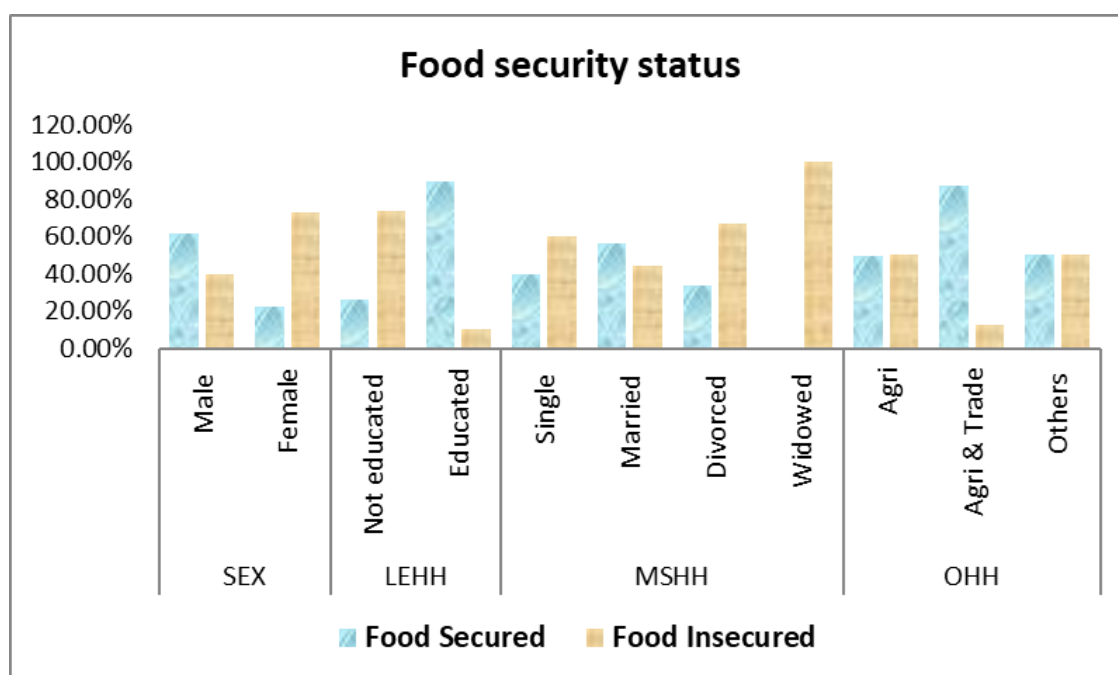
88% were married, 8% were single, 2% were divorced, and 2% were widowed in terms of their marital status. Regarding their occupations, 89.7% of the household respondents depended solely on agri-

culture, 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%), unable to supplement their crop production using traditional irrigation schemes (87.19%), not involved in cooperative activities (83.13%), unable to obtain veterinary services (80%), unable to prepare and apply fertilizers (86.56%), unable to use oxen to plow their land (66.25%), unable to access credit services (82.19%), and unable to purchase and apply chemical pesticides (67.50%) (Figure 3).

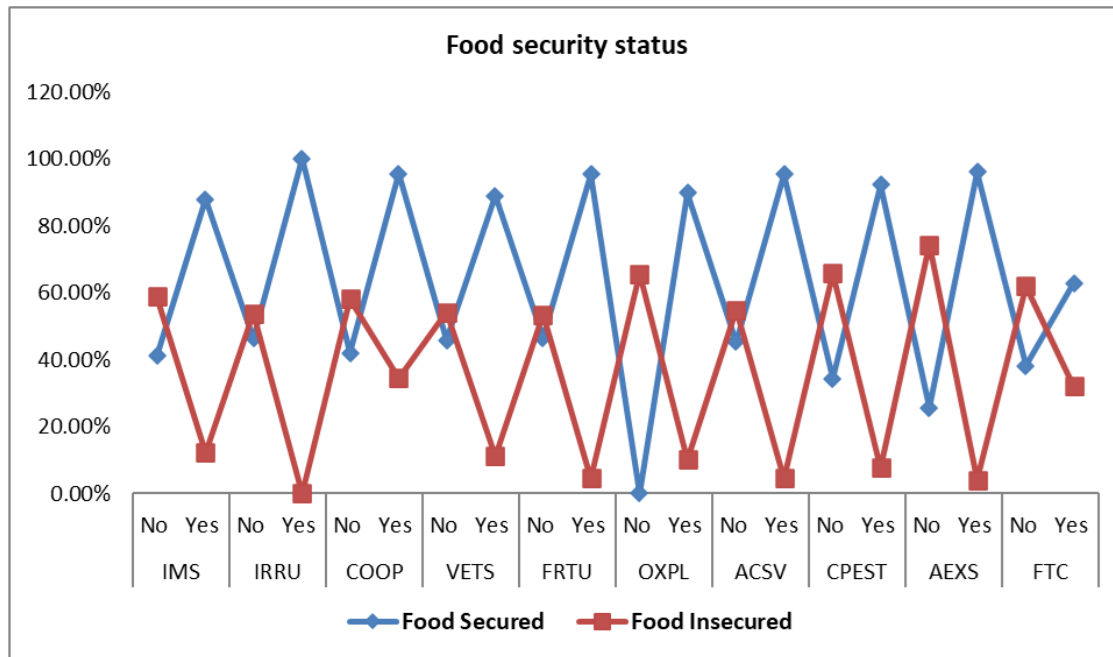


**Figure 2.** Descriptive statistics on the food security status of respondents

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 veterinary 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 determined based on the food consumption score categories previously established by the WFP (2008). In total, 22 explanatory variables were fitted to the specified model among, which 10 showed statistical significance at varying levels of probability and magnitude of influence.

The overall fitness of the model was checked using post-estimation tests (linktest, estat gof, estat classification, lsens, lroc). The link test result showed significant  $\hat{\rho}$  ( $p < 0.01$ ) and insignificant  $\hat{\rho}^2$  ( $p < 0.374$ ), indicating a perfect link between variables with no transformation, and the chi-square test was significant at 1% probability ( $\text{prob} > \chi^2 = 0.0001$ ). The goodness-of-fit test also estimated 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 bee-

hives, formal education, agricultural land size, oxen plowing, livestock herds, access to extension support, and working family members were positively associated with food security. However, the age of the household head and the use of chemical pesticides had significant negative predictive effects on food security status.

The results in Table 2 show that household age is negatively related to household food security. The negative coefficient indicates the existence of a statistically significant ( $p < 0.5$ ) but inverse relationship between age and the food security status of households. 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). These findings are consistent with those of similar studies conducted in other parts of Brazil (Mohammed *et al.*, 2021; Sani & Kemaw, 2019b; 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 re-

search, 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 association between family size and food security is seldom positive in food security studies. However, the results of this study reveal a positive and statistically significant relationship at the 10% probability level. Accordingly, a unit increase in the number of families increases the food security

status of households by 0.6119 units, while the other variables are held constant. The justification for this could be that households with large family members, given that they are active adults, can supply more labor for agricultural activities, which can increase production and productivity. In line with this, the study results of Alemu (2013) revealed that having more family members helps provide more labor for production and has a positive association with the food security status of households.

**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 insecure)=96.67%		LR $\chi^2(2)$ = 372.00	
Correctly classified=96.25%		Prob > $\chi^2$ = 0.0000	

Source: Own survey data

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

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, the education status of the households was significant at the 1% probability level, with a predicted positive 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 a positive coefficient that was statistically significant 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).

Equally crucial as the TLU, is the oxen plowing of farms that are assumed to have a positive influence on food security. Nevertheless, few households had access to and experience with plowing with oxen in the study area; those exercising the practice benefited the most comparably. Meeting this assumption, plowing land with oxen enables farmers to be 0.9674 units more likely to be food secure than those who do not. Furthermore, as hypothesized to have a positive influence on household food security, farm income is predicted to be highly significant ( $p < 0.003$ ) in influencing food security status in the study area. Consequently, the food security status of households tends to increase by a factor of 1.0001 as farm income increases by one unit. Pearson's correlation results revealed a strong and positive relationship (81.10%) between farm income and household food security status. The results of this research are in agreement with the findings of Awoke *et al.* (2022), Dagne (2016), Hussein & Janekarnkij (2013) and Etxegarai-Legarreta and Sanchez-Famoso (2022), who reported a positive and significant influence of on-farm income on the food security of rural households in different parts of Ethiopia.

Most food security studies in Ethiopia have focused less on and incorporated factors related to apirary activities in general, and none has been performed specifically in the research area. Beekeeping tends to be complementary to agriculture and allows it to generate additional income for its producers (Hussein & Janekarnkij, 2013).

Apart from generating income and serving as direct food, the existence of apirary 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 ani-

mal 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 hypothesized, keeping the other variables constant at their zero mean and unit standard deviation, the number of beehives owned had a positive and significant effect on determining household food security status at the 5% probability level. A greater probability of having more beehives increases food security by 0.1014 units. Empirical evidence from research conducted in southern Ethiopia by Tarekegn & Ayele (2020) agrees that increasing the number of beehives by 1% is likely to increase honey production by 10.14%, increasing the likelihood of becoming food secure. 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. Thus, this factor was expected to have a positive and significant impact on household food security.

The results of the logit model indicate that participating in agricultural extension packages is predicted to increase the likelihood of becoming food secure by 0.3435 units compared to non-participating units, which is statistically significant at the 1% level, all else being equal. Similarly, Awoke *et al.* (2022) and Sani and Kemaw (2019b) concluded that technical support for farmers plays an important role in enhancing the food security status of smallholders. It was anticipated that inputs such as fertilizers, pesticides, artificial insemination, and improved seeds would play a substantial role in improving 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 study aimed to identify the determinants and measure the food security status of rural households in the study area. It sought to examine the factors that govern food security in the region. Moreover, the results of this research are consistent with similar studies conducted in Ethiopia as well as across the world.

The findings indicated that 53% and 47% of the households were food secure and insecure, respectively. While pesticide use and the age of households negatively affected food security status, beehives, formal education, landholding, oxen plowing, livestock ownership, farm income, extension support, and family size had a significant and positive impact on food security status.

The study revealed 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 the potential 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

The coordinated effort among federal, regional, and local-level government agencies 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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## Ethics approval and consent to participate:

This study was approved by the Institutional Review Board (IRB) of the College of Development Studies (CoDS) of Addis Ababa University on 24/08/2023 (Reference Number: spe/e/c/28/07/2023).

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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 demon-

strated success in ecological preservation, promoting sustainable land use practices, and increasing resilience to climate change impacts (Nick & Woldemanna, 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 socioeconomic 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; Katusime, 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°17' and 9°29'N, and longitudes 41°12' and 41°56'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°C and 26.6°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 Febru-



ary (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 (SLMP II), 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.

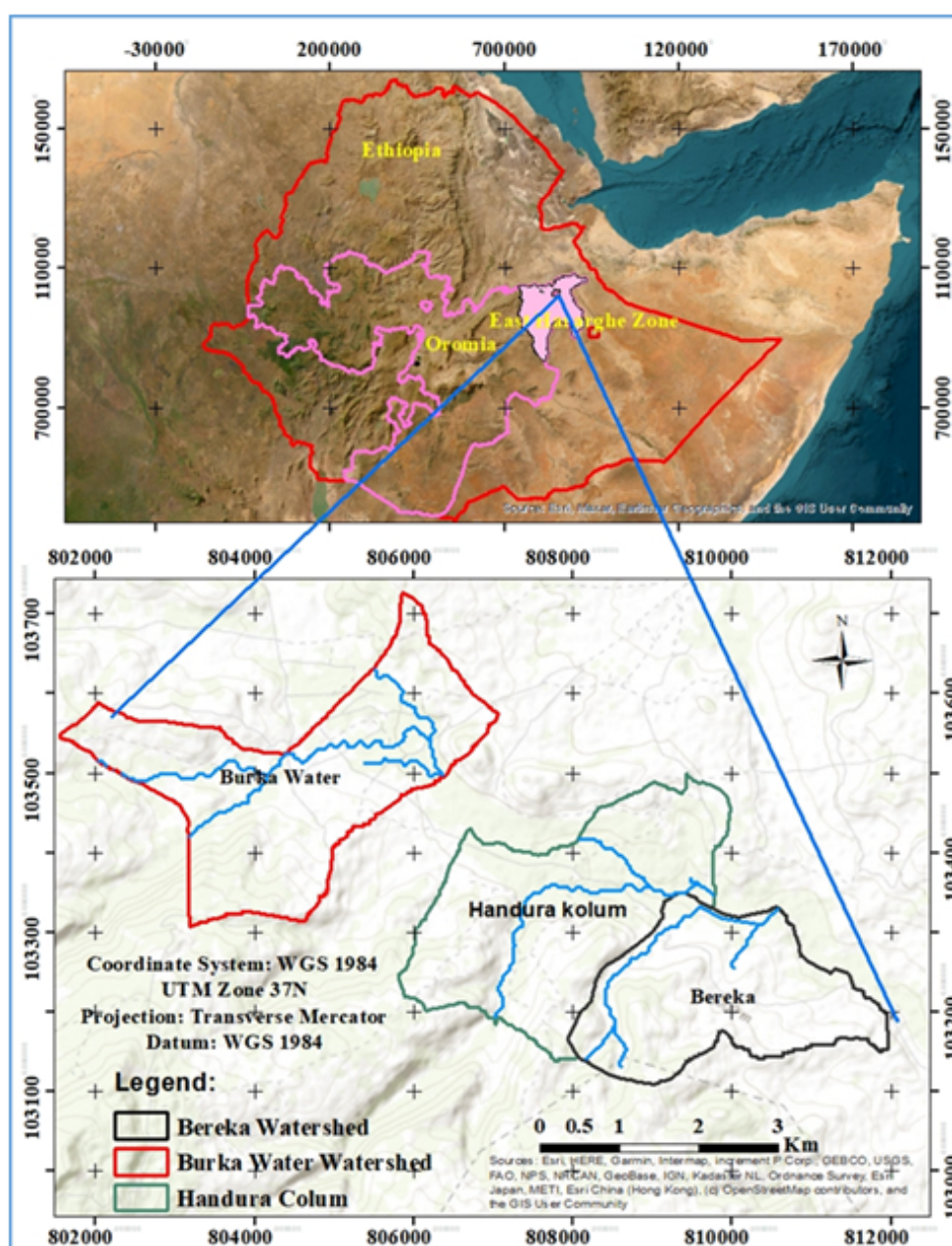


Figure 1. Map of the study area

## 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.

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

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:

$$SS_{pk} = \frac{S}{1 + \frac{S-1}{P_k}} \quad (2)$$

Where:  $SS_{pk}$  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

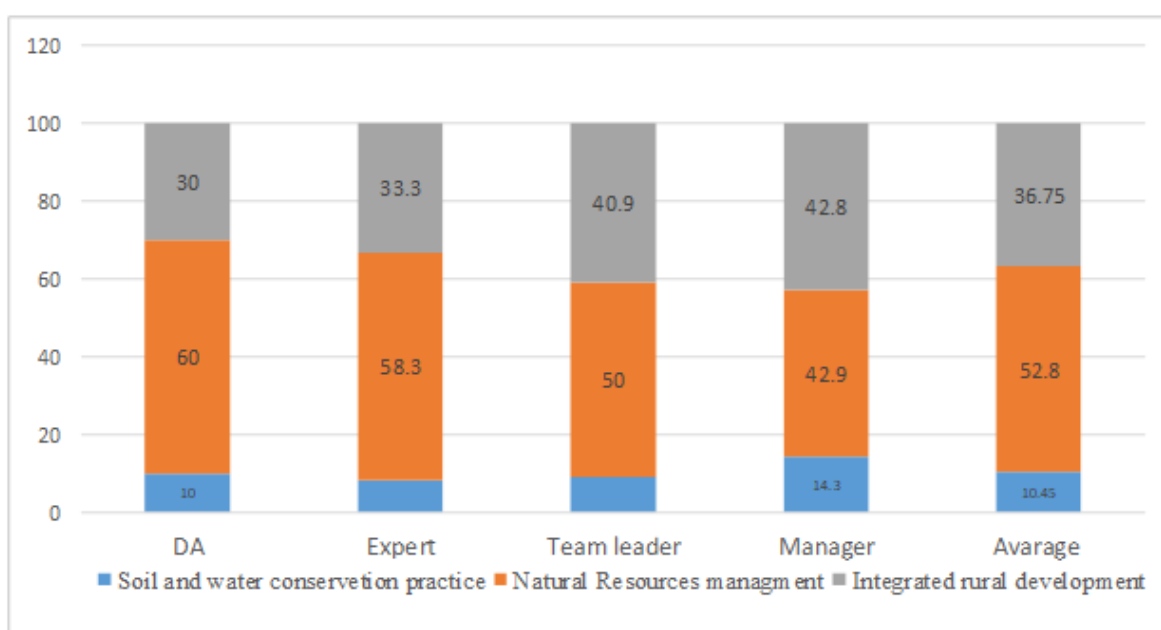
Sources: 2021-2022 survey

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 un-

derscore 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 asso-

ciations 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

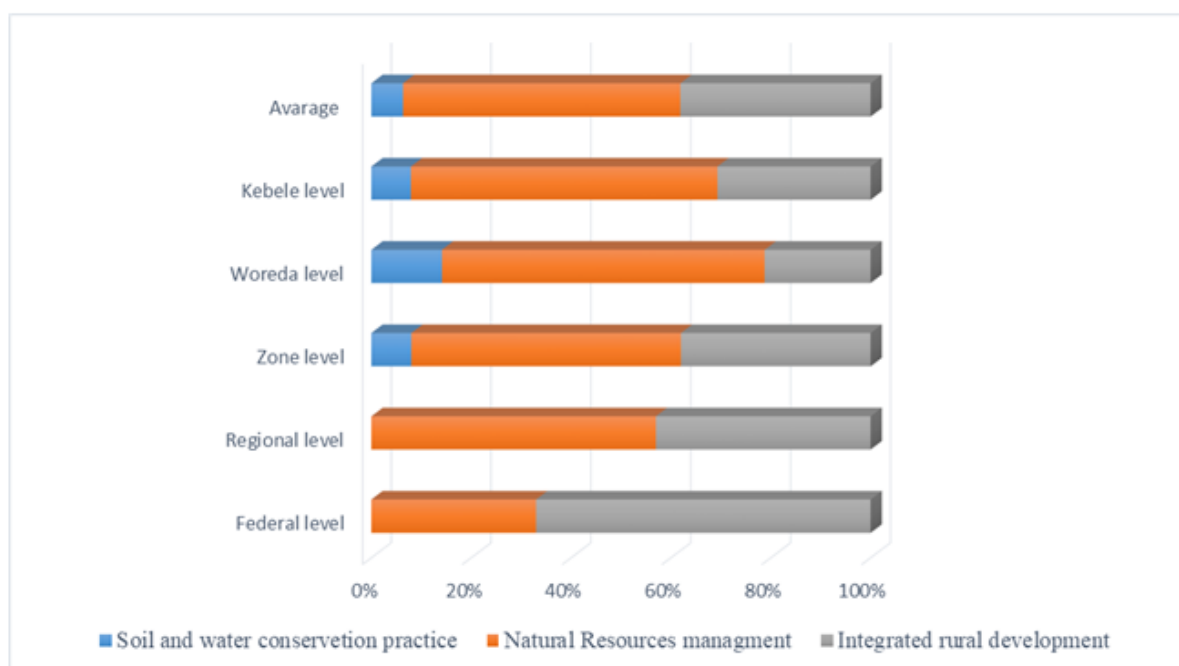
	Baraka PNSP-PW N=118	Burka Water_SLMP N=107	Adhura kosum_Regular N= 112	Over all N=337	Pearson Chi- Square	Df	P- value
Soil and water conservation	50 (42.4%)	30 (28.%)	52 (46.4%)	132 (39.2%)	9.900	4	0.042
Natural Resources Management	58 (45.8% )	58 (54.2%)	50 (44.6 %)	162 (48.1)			
Integrated rural development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

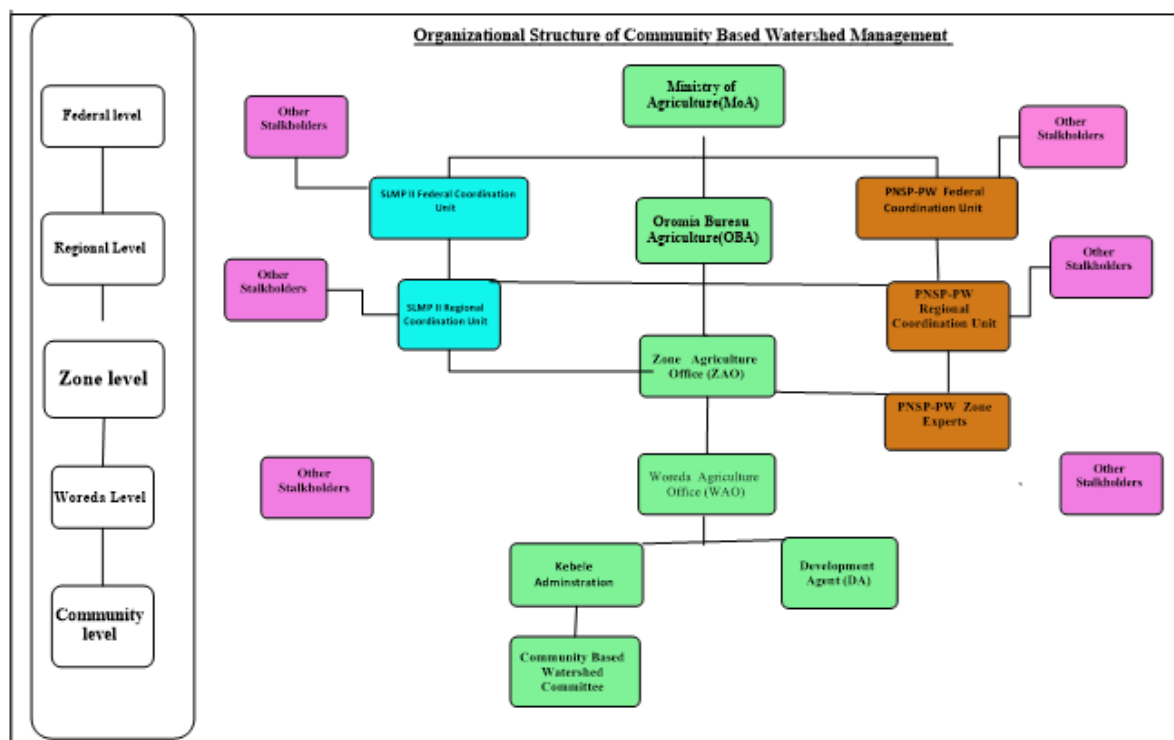
This section examines how the three micro-watershed approaches handled watershed management practices at the local level and the institutional structure in place across different governance levels. At the federal level, the Ethiopian Federal Democratic Republic amended Proclamation No. 1263/2021, showing 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.

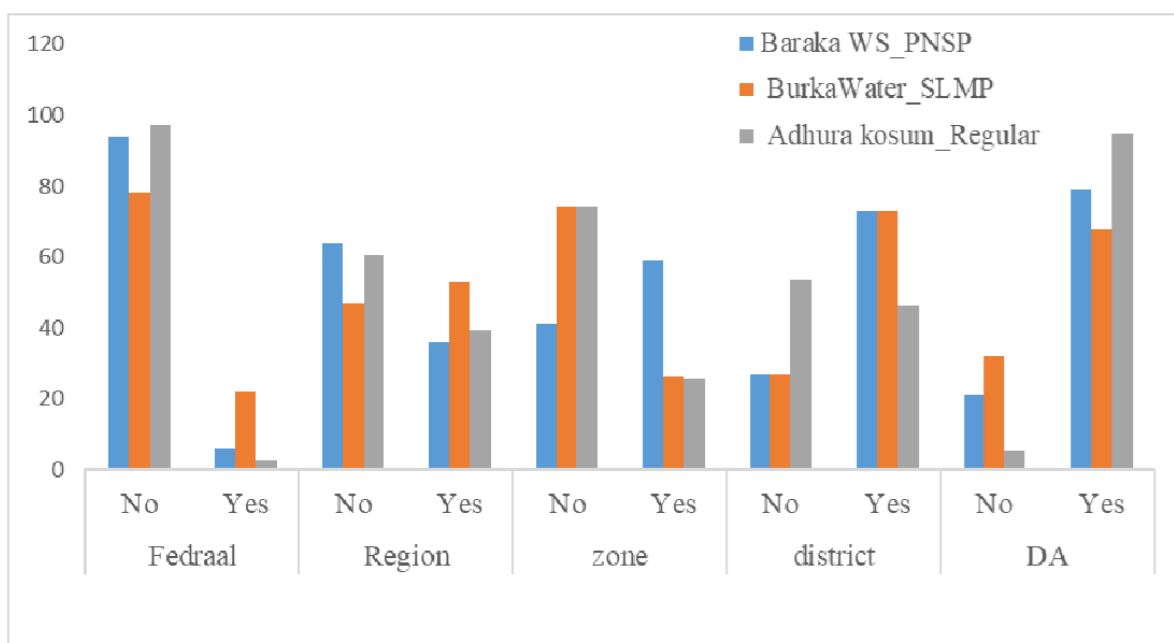
Despite the structured framework for watershed management established across various government hierarchies, the household survey indicated significant gaps in the participation and coordination of federal and regional entities at the village level (see Figure 5). A majority of participants (approximately 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

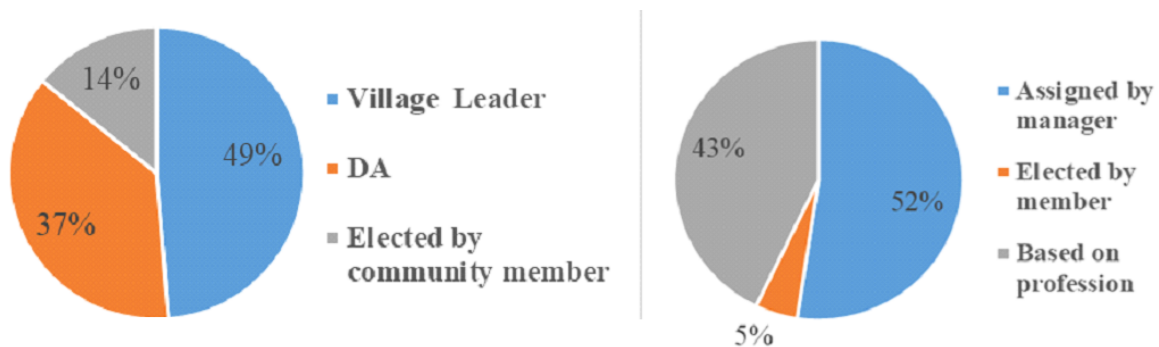
specific integrated watershed management strategy relied on the engagement of higher-level government authorities and their commitment to their responsibilities (Nigussie *et al.*, 2018; Abuto, 2009).



**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

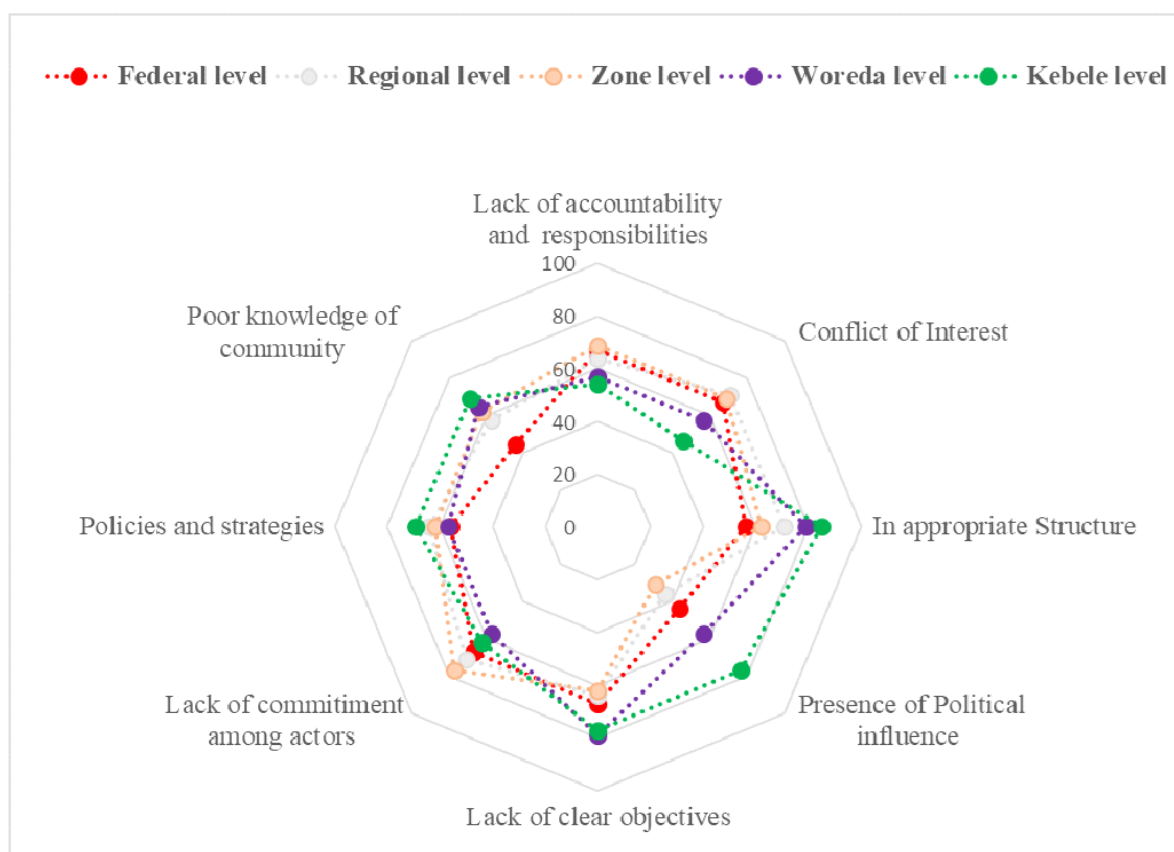
The success or failure of watershed management may depend on the degree of responsibility that partners



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 differ-

ent 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

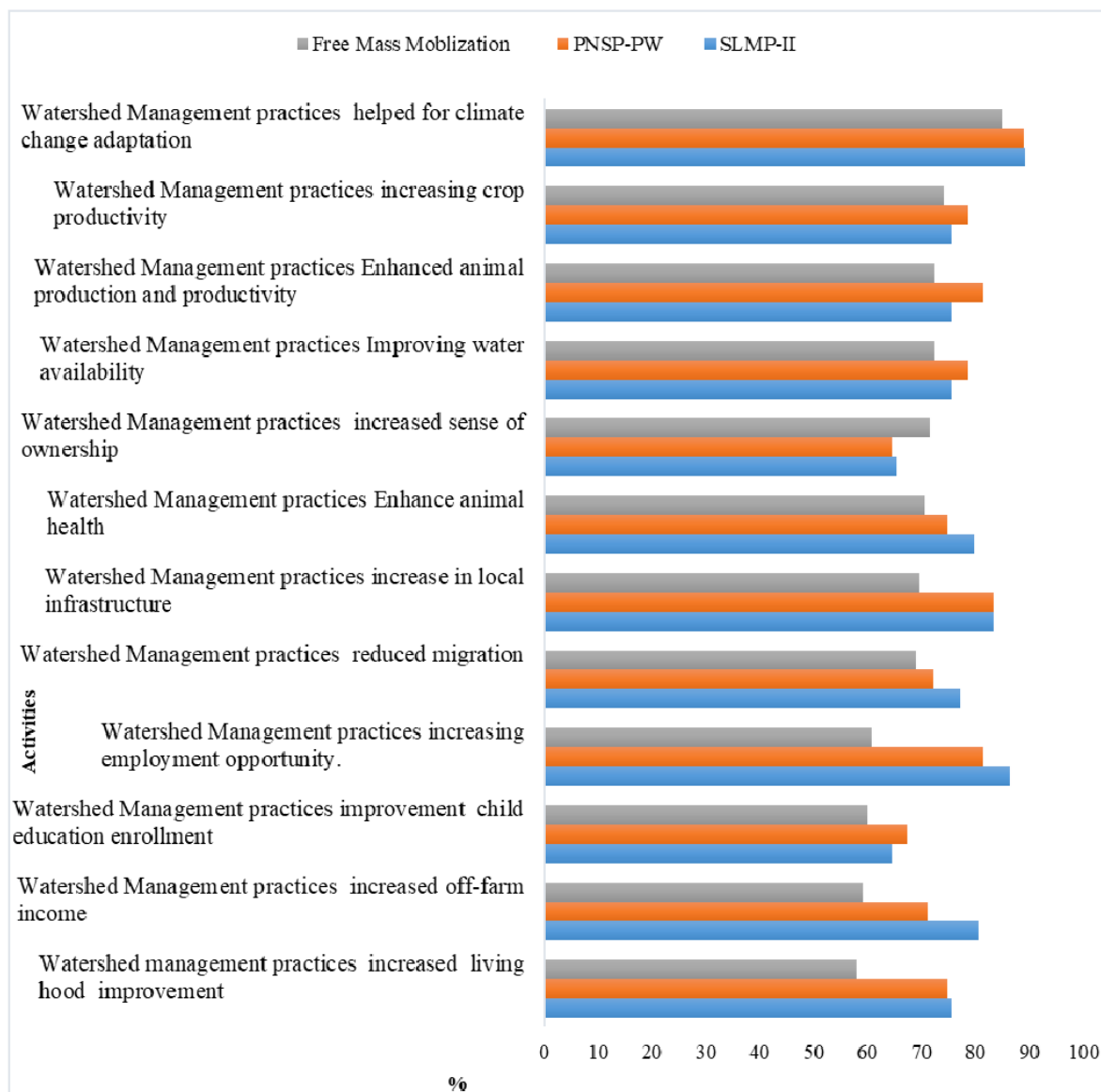
The study explored how watershed management can improve food security by examining factors such as water availability, soil fertility, and agricultural practices from the perspective of household perceptions. A majority of participants (72.3%) in the mass mobilization programs, including PNSP-PW (75.4%) 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, Dana-cioglu 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 Developmen-

tal 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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Data will be made available on request.

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