

Climate-Smart Food, Fodder, and Cash Production through Acacia mearnsii– Based Rotational Agroforestry Systems for Building Resilient Communities and Sustainable Livelihoods in the Upper Blue Nile Basin, Ethiopia

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Abstract

Land degradation and climate change are seriously undermining food security, livestock feed, and household incomes across the Ethiopian Highlands. In the Upper Blue Nile Basin, over 60% of former cropland has been converted to *Acacia mearnsii*-based agroforestry through the locally evolved rotational system, largely driven by rising urban demand for charcoal and the need for sustainable land restoration. However, empirical evidence on its multiple benefits remains limited. This study examines the potential of short-rotation *Acacia mearnsii* agroforestry to enhance climate-smart food, fodder, and cash production while building resilient communities and sustainable livelihoods. Data were gathered from 148 randomly selected smallholder farmers, biophysical assessments across 30 plots, 7 key informant interviews, 6 focus group discussions, and field observations. The findings reveal a triple-win transformation across ecological, economic, and social dimensions. Ecologically, the system improved soil health significantly: soil organic carbon rose by 44% (from 1.8% to 2.6%), and available phosphorus increased by 162% (from 4.3 ppm to 11.3 ppm). At charcoal production sites, soil pH increased by one unit (equivalent to applying 4–5 tons of lime per hectare). Intercropping teff, wheat, and barley within the rotational framework boosted crop productivity fourfold, with a 75% increase in food output during the first rotation year (1.65 t ha⁻¹ vs. 0.95 t ha⁻¹; $p < 0.01$). Economically, the integrated cash-fodder-food system contributes 82% of average annual household income (ETB 86,352), reflecting a 3.2-fold increase in income diversification and a 35% reduction in drought-year income volatility. Fodder alone generates ETB 3,300 ha⁻¹, while charcoal production creates employment opportunities across gender and age groups. Socially, the overall livelihood index of farmers increased from 0.47 (pre-*Acacia*) to 0.71 in the post-*Acacia* period, with financial capital showing the greatest improvement (+ 0.43). Adoption follows a locally optimized 4–5 year rotational cycle (Year 1: teff; Year 2: fodder; Years 4–5: charcoal), spreading through farmer-to-farmer networks. We conclude that *Acacia mearnsii*-based agroforestry holds strong potential for advancing climate-smart food, fodder, and cash production, while fostering resilient food systems and sustainable livelihoods in the Upper Blue Nile Basin. Realizing this potential will require integrated disease management, nutrient recycling strategies, and supportive policies to scale this indigenous climate-resilient innovation.

Introduction

The Ethiopian Highlands, particularly the Upper Blue Nile Basin, face critical challenges of land degradation, declining soil fertility, and climate variability that threaten the livelihoods of millions of smallholder farmers (Mekonnen et al., 2023; Nigussie et al., 2021). Continuous cereal mono-cropping, population pressure, and unsustainable land management practices have resulted in severe soil erosion, nutrient depletion, and reduced agricultural productivity (Kim et al., 2022; Tadele et al., 2024). These challenges are compounded by climate change, which increases the frequency and severity of droughts, undermining food security and household incomes (Afework et al., 2024; Nigussie & Abele, 2025).

In response to these challenges, smallholder farmers in the northwestern highlands of Ethiopia have developed an innovative, locally-evolved land use system: the *Acacia mearnsii*-based rotational

agroforestry system (Mekonnen et al., 2023; Wondie & Mekuria, 2017). This system, known locally as the "Tanguay" system, integrates nitrogen-fixing *Acacia mearnsii* trees with food crops, livestock fodder, and charcoal production in a carefully managed rotation (Kim et al., 2022; Mekonnen et al., 2023). The system has expanded rapidly from negligible coverage in 1993 to 24.53% of the landscape by 2022 driven primarily by farmers' needs to restore soil fertility, generate income, and meet fuelwood demand (Wondie & Mekuria, 2017; Worku et al., 2023).

The *Acacia mearnsii*-based rotational system follows a structured 4–5 year cycle (Mekonnen et al., 2023; Shiferaw et al., 2026). In the first year, teff (*Eragrostis tef*) is intercropped with young *Acacia mearnsii* seedlings. The teff provides immediate food security and income while the trees establish. During the second year, fodder grasses are intercropped between the *Acacia* rows, providing livestock feed and increasing land productivity. In years three and four, the *Acacia mearnsii* trees mature, enriching soil through nitrogen fixation and stabilizing the land. By year's four to five, the trees are harvested, and charcoal production is carried out on-site using traditional kilns. After harvest, the land is replanted, restarting the rotation. This rotational approach has multiple benefits. It combines short-term food production with medium-term livestock fodder and long-term cash income from charcoal, providing farmers with diversified income streams and enhanced resilience to economic and climatic shocks (Nigussie et al., 2021; Mekonnen et al., 2023).

Although the *Acacia mearnsii* system has expanded rapidly, quantitative evidence on its comprehensive ecological, economic, and social benefits remains limited (Afework et al., 2024; Mekonnen et al., 2023). Previous studies have examined specific aspects: soil fertility improvements (Kim et al., 2022; Tadele & Adgo, 2024; Beshir et al., 2025), economic benefits (Nigussie et al., 2020; Mekonnen et al., 2023), and livelihood impacts (Nigussie et al., 2021; Afework et al., 2024). However, a holistic assessment integrating all three dimensions—food production, fodder provision, and cash generation within the context of climate-smart agriculture is lacking. The objectives of this study are to examine the effects of the *Acacia mearnsii*-based rotational system on soil properties and crop productivity; evaluate the economic benefits of the system, including income generation and diversification; assess the impact on household livelihoods and community resilience; and identify challenges and opportunities for scaling and sustainability. This study contributes to the growing literature on agroforestry as a climate-smart agricultural practice, providing evidence-based recommendations for policy and practice in Ethiopia and similar contexts.

Materials and Methods

Study Area Description

This study was conducted in Fagita Lekoma District, Awi Zone, in the northwestern highlands of Ethiopia. The district is located between 10°57'–11°11' N and 36°40'–37°05' E, with an elevation ranging from 1,800 to 2,900 m above sea level. The total area of the district is 67,950 ha (Mekonnen et al., 2023). The area has a subtropical highland climate with a bimodal rainfall pattern. The main rainy season extends

from June to September, with a shorter rainy season from March to April. Average annual rainfall ranges from 1,200 to 1,800 mm, and mean annual temperatures range from 15°C to 22°C. The predominant soil type is Vertisol, which is characterized by high clay content and, in many areas, soil acidity a major constraint to crop production (Tadele et al., 2024; Amare et al., 2022). The study area is representative of the broader Upper Blue Nile Basin, where *Acacia mearnsii*-based agroforestry has expanded rapidly. The district's population is predominantly engaged in mixed farming systems, combining crop production, livestock rearing, and, increasingly, tree-based enterprises (Mekonnen et al., 2023; Wondie & Mekuria, 2017).

Research Design

A mixed-methods research design was employed, combining quantitative household surveys, biophysical assessments, and qualitative methods. This approach was chosen to provide a comprehensive understanding of the system's impacts across ecological, economic, and social dimensions.

Household Survey and Sampling

A total of 148 smallholder farmers were randomly selected from households practicing the *Acacia mearnsii*-based rotational system. The sample size was determined using Yamane's formula (1967) with a 95% confidence level and 8% margin of error. Sampling was stratified by village to ensure representation across the district. Data were collected using a structured questionnaire covering household demographics and assets, land use and management practices, crop and livestock production, income sources and levels, participation in charcoal production and marketing, and perceived benefits and challenges of the system.

Biophysical Assessments and Sampling

Biophysical assessments were conducted across 30 plots representing different land use types and rotation stages. The plot types included teff monocropping system (control), teff–*Acacia* intercropping (Year 1), fodder–*Acacia* intercropping (Year 2), *Acacia* plantation (Years 3–4), and charcoal production sites (post-harvest).

Soil sampling and analysis

Soil samples were collected at 0–10 cm, 10–20 cm, and 20–40 cm depths using a standard auger. For each plot, five composite samples were collected from the center and four corners. Soil properties analyzed included soil organic carbon (SOC) using the Walkley-Black method, total nitrogen (TN) using the Kjeldahl method, available phosphorus using the Olsen extraction method, soil pH using a pH meter

(1:2.5 soil-water ratio), exchangeable cations (K, Ca, Mg, Na) using ammonium acetate extraction, and black carbon content (for charcoal production sites).

Crop and biomass productivity assessment

Crop productivity was assessed by measuring teff grain yields from 1 m² quadrats placed randomly in each plot, with five replications per treatment. For fodder plots, biomass was measured by harvesting and weighing vegetation from 1 m² quadrats.

Qualitative Data Collection

Qualitative data were collected through key informant interviews with seven key informants, including district agricultural officers, extension agents, and experienced farmers. Six focus group discussions were held with separate groups of male farmers, female farmers, and mixed groups. Direct field observations were conducted to document the system's spatial organization, tree-crop interactions, and charcoal production practices.

Statistical and Economic Analyses

Descriptive statistics (means, standard deviations, frequencies, and percentages) were used to summarize household characteristics, income sources, and land use patterns. One-way Analysis of Variance (ANOVA) was used to compare soil properties and crop yields across land use types. Pairwise comparisons were performed using Tukey's Honestly Significant Difference (HSD) test. Statistical significance was determined at $p < 0.05$. The Sustainable Livelihoods Framework (SLF) was used to assess changes in livelihood capital indices (natural, physical, financial, human, and social) between pre- and post-*Acacia* periods. Capital indices were calculated based on household asset scores following the methodology of Afework et al. (2024). The Herfindahl-Hirschman Index (HHI) was used to measure income diversification, where lower HHI values indicate greater diversification. Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR) were calculated for each land use system following standard financial analysis methods (Mekonnen et al., 2023; Alemayehu et al., 2026).

Qualitative Data Analysis

Thematic analysis was used to identify key themes from interview and focus group transcripts. Transcripts were coded using NVivo software, and themes were organized around benefits, challenges, and opportunities of the system.

Results

Soil Property Improvements

The *Acacia mearnsii*-based rotational system significantly improved soil properties compared to conventional teff monocropping (Table 1). The improvements were most pronounced in the teff–*Acacia* intercropping system and at charcoal production sites. Soil organic carbon content increased by 44% from 1.8% (sole teff) to 2.6% (teff–*Acacia* intercropping). At charcoal production sites, SOC reached 3.3% an 83% increase over the control. These findings align with Kim et al. (2022), who reported SOC increases of 112–169% in teff–*Acacia* systems compared to monocropping, and Beshir et al. (2025), who found significant SOC increases in the teff–*Acacia*–charcoal rotation system. The SOC accumulation is attributed to leaf litter and root decomposition, as *A. mearnsii* produces substantial leaf litter and fine root biomass, which decompose and contribute to soil organic matter. The tree's nitrogen-fixing capacity enhances soil fertility, promoting greater biomass production and organic matter inputs. Additionally, fire and charcoal residues from on-site production contribute black carbon and organic matter to the soil (Kim et al., 2022; Amare et al., 2022).

Table 1
Soil Properties by Land Use Type

Land Use Type	SOC (%)	TN (%)	Avail. P (ppm)	pH (H ₂ O)	Exchangeable K (cmol/kg)
Sole Teff (Control)	1.8 ± 0.2a	0.16 ± 0.02a	4.3 ± 0.8a	5.1 ± 0.3a	0.31 ± 0.05a
Teff– <i>A. mearnsii</i> Intercrop	2.6 ± 0.3b	0.21 ± 0.03b	11.3 ± 1.2b	5.6 ± 0.2b	0.42 ± 0.04b
Fodder– <i>A. mearnsii</i> Intercrop	2.8 ± 0.3b	0.22 ± 0.02b	10.8 ± 1.5b	5.7 ± 0.3b	0.45 ± 0.05b
Charcoal Production Site	3.3 ± 0.4c	0.25 ± 0.03c	18.5 ± 2.3c	6.1 ± 0.4c	0.58 ± 0.06c

Mean values (± standard deviation) of soil properties at 0–20 cm depth across different land use types. Different superscript letters within a column indicate significant differences at $p < 0.05$ (Tukey's HSD test). Source: Field data, 2024–2025.

Available phosphorus increased by 162% from 4.3 ppm (sole teff) to 11.3 ppm (teff–*Acacia* intercropping). At charcoal production sites, available P reached 18.5 ppm a remarkable 330% increase over the control. This finding is consistent with Kim et al. (2022), who reported P increases of 687% at charcoal production sites, and Amare et al. (2022), who found P increases of 92–112%. The increased P availability is likely due to the increase in soil pH (from 5.1 to 5.6 in intercropped systems, and to 6.1 at charcoal sites) which reduces P fixation by aluminum and iron oxides. Biochar from charcoal production may directly contribute available P and enhance P cycling, while increased organic matter may chelate P-fixing cations, making P more available. Soil pH increased from 5.1 (sole teff) to 5.6 (intercropping) and to 6.1 at charcoal production sites. Amare et al. (2022) reported that the *Acacia* system can raise soil pH by approximately one unit, equivalent to applying 4–5 tons of lime per hectare. This pH amelioration is particularly important in acid soils, where aluminum toxicity limits crop production. Total nitrogen

increased from 0.16% (sole teff) to 0.21% (intercropping) and 0.25% at charcoal sites. Kim et al. (2022) reported STN increases of 100–131% in agroforestry systems compared to teff fields. The *A. mearnsii*'s nitrogen-fixing ability, combined with enhanced biomass production and organic matter inputs, accounts for these increases.

Crop and Fodder Productivity

The *Acacia mearnsii*-based rotational system substantially improved crop and fodder productivity compared to sole cropping systems (Table 2). Teff grain yields increased by 75%—from 0.95 t ha⁻¹ (sole teff) to 1.65 t ha⁻¹ (teff–*Acacia* intercropping) ($p < 0.01$). This finding is consistent with Tadele et al. (2024), who reported increased teff productivity following *A. mearnsii*-based fallow, and with Shiferaw et al. (2026), who documented a fourfold increase in crop productivity in the *A. mearnsii* system. The mechanisms underlying this productivity increase include enhanced soil fertility, particularly N and P availability, which directly supports crop growth. The *Acacia* trees moderate temperature extremes and reduce wind speed, potentially reducing crop water stress. Tree root systems improve soil structure, water infiltration, and moisture retention. Additionally, biological nitrogen fixation by *A. mearnsii* may supply N to the intercropped teff through root exudation and mycorrhizal networks.

Table 2
Crop and Fodder Productivity by Land Use Type

Land Use Type	Teff Yield (t ha ⁻¹)	Fodder Biomass (t ha ⁻¹)	Total Food Output (t ha ⁻¹)
Sole Teff (control)	0.95 ± 0.12a	NA	0.95 ± 0.12a
Teff– <i>A. mearnsii</i> Intercrop (year 1)	1.65 ± 0.18b	NA	1.65 ± 0.18b
Sole Fodder (Control)	NA	2.10 ± 0.30a	NA
Fodder– <i>A. mearnsii</i> Intercrop (year 2)	NA	7.60 ± 0.85b	NA

Mean yields (± standard deviation) across different land use types. Different lowercase letters within a column indicate significant differences at $p < 0.05$ (Tukey's HSD test). NA = not applicable (crop type not grown in that system). Source: Field data, 2024–2025.

Fodder biomass in the fodder–*Acacia* intercropping system (7.60 t ha⁻¹) was 3.6 times higher than sole fodder production (2.10 t ha⁻¹) ($p < 0.01$). The shading provided by *Acacia* trees creates favorable conditions for fodder grass growth, while the improved soil fertility enhances biomass production. This result is consistent with Mekonnen et al. (2023), who reported that fodder–*Acacia* intercropping provided 11 times more income than sole fodder production.

Economic Benefits

The *Acacia mearnsii*-based system generated substantial economic benefits, outperforming sole cropping alternatives across multiple indicators (Table 3). The integrated Teff–*Acacia* intercropped system generated the highest total revenue (ETB 278,500 ha⁻¹ over 5 years), followed by the Fodder–*Acacia* system (ETB 269,500 ha⁻¹). The Teff–*Acacia* intercropping provided 1.3 times more income than sole teff and 1.2 times more income than sole *Acacia*, while the Fodder–*Acacia* intercropping provided 11 times more income than sole fodder. These findings align with Mekonnen et al. (2023), who reported similar income multipliers in the same study area. The Teff–*Acacia* intercropping system had the highest NPV (ETB 38,820 ha⁻¹), followed by Fodder–*Acacia* intercropping (ETB 36,490 ha⁻¹). These values far exceeded sole teff (ETB 5,431 ha⁻¹) and sole fodder (ETB 1,450 ha⁻¹). The NPV of sole *Acacia* (ETB 26,683 ha⁻¹) was also substantial, confirming the profitability of tree-based systems even without intercropping (Nigussie et al., 2020).

Table 3
Economic Performance by Land Use Type (per ha, 5-year rotation)

Land Use Type	Total Revenue (ETB)	Total Cost (ETB)	Net Revenue (ETB)	NPV (ETB)	BCR	IRR (%)
Sole Teff	69,850	48,250	21,600	5,431	1.17	28
Sole Fodder	24,500	18,000	6,500	1,450	1.08	14
Sole <i>A. mearnsii</i>	215,000	148,500	66,500	26,683	1.53	58
Teff– <i>A. mearnsii</i> Intercrop	278,500	195,000	83,500	38,820	1.62	68
Fodder– <i>A. mearnsii</i> Intercrop	269,500	186,000	83,500	36,490	1.60	66

Economic indicators for different land use types. NPV calculated using a 10% discount rate. Currency: 1 USD ≈ 150 ETB (2025 approximate rate). Source: Field data and financial analysis, 2024–2025.

All systems except sole fodder (BCR = 1.08) had BCR > 1.5, indicating efficient investment. Teff–*Acacia* intercropping had the highest BCR (1.62), meaning that for every 1 ETB invested, farmers gained 1.62 ETB in present value benefits. These results are consistent with financial evaluation studies (Alemayehu et al., 2026; Nigussie et al., 2020). The IRR was highest for Teff–*Acacia* intercropping (68%), followed by Fodder–*Acacia* (66%) and sole *Acacia* (58%). These high IRR values indicate that the systems are highly profitable relative to alternative investments. By comparison, conventional agriculture (sole teff) had an IRR of only 28% (Nigussie et al., 2020). The integrated system contributes 82% of average annual household income (ETB 86,352), compared to 42% from agriculture in the pre-*Acacia* period. Income diversification increased by 3.2-fold, and income volatility during drought years was reduced by 35% due to the diversified income streams from crops, fodder, and charcoal (Shiferaw et al., 2026).

Livelihood Impacts

The *Acacia meurnsii*-based system significantly improved household livelihoods across multiple dimensions (Table 4). Financial capital showed the greatest improvement (+ 0.43). Households reported increased income from charcoal sales, improved crop yields, and diversified income sources. The integrated system provided additional cash income that was used for education, healthcare, and reinvestment in agriculture (Afework et al., 2024; Nigussie et al., 2021). Natural capital improved by + 0.25, with improvements in soil fertility, availability of fuelwood, and fodder resources.

Farmers perceived that *Acacia* plantations improved soil health, providing fodder and fuelwood year-round (Mekonnen et al., 2023). Human capital increased by + 0.25, as increased income from the system allowed investment in education and healthcare. Additionally, skills in agroforestry management and charcoal production were transferred through farmer-to-farmer networks. Physical capital increased by + 0.24, with investment in livestock, farm tools, and household assets rising as income increased. Charcoal production required investments in kilns and tools, contributing to physical asset accumulation. Social capital improved by + 0.06, with adoption of the system spreading through social networks and farmer-to-farmer knowledge transfer. The overall livelihood index increased by 0.24 (from 0.47 to 0.71), representing a substantial improvement in household wellbeing (Afework et al., 2024). This confirms the system's effectiveness in building resilient communities.

Table 4
Livelihood Capital Indices

Capital Type	Pre-Acacia	Post-Acacia	Change
Natural Capital	0.42	0.67	+ 0.25
Physical Capital	0.31	0.55	+ 0.24
Financial Capital	0.28	0.71	+ 0.43
Human Capital	0.38	0.63	+ 0.25
Social Capital	0.62	0.68	+ 0.06
Overall Livelihood Index	0.47	0.71	+ 0.24

Table caption: Livelihood capital indices before and after adoption of the *Acacia* system. Indices calculated based on household asset scores following Afework et al. (2024). Source: Field survey (n = 148).

System Adoption and Farmer Perceptions

Farmers were motivated to adopt the *Acacia* system primarily by income generation, as the need for additional cash income, particularly from charcoal, was the primary driver. Urban demand for charcoal has created a lucrative market (Nigussie & Abele, 2025). Soil fertility restoration was another key driver, as farmers perceived that *Acacia* trees improved soil fertility, enabling productive cropping after the fallow period (Tadele et al., 2024; Amare et al., 2022). The system also provided domestic fuelwood, reducing time spent collecting firewood and energy costs, and fodder from intercropping and tree pods provided year-round livestock feed. Adoption follows a 4–5 year rotational cycle optimized locally: Year 1

involves teff intercropping; Year 2 involves fodder intercropping, and Years 4–5 involve charcoal production. This cycle provides short-term food security (Year 1 teff), medium-term livestock feed (Year 2 fodder), and long-term cash income (Years 4–5 charcoal).

Qualitative data from focus groups and interviews revealed that farmers reported improved food security, increased income, enhanced soil fertility, and reduced vulnerability to drought. Challenges identified included pests and diseases (particularly wattle rust), high production costs, limited market access, negative health impacts from traditional charcoal production, and gender-based disparities in resource access. Women play important roles in fodder collection and fuelwood gathering, while men are primarily involved in charcoal production and marketing. Access to benefits is often gendered, with women having less control over tree products (Afework et al., 2024). The system has spread rapidly through farmer-to-farmer networks. Land use change data show that cropland decreased from 67% to 30%, grazing land from 19% to 12%, while *Acacia* woodlots increased to 42.1% of the landscape (Wondie & Mekuria, 2017; Worku et al., 2023).

Discussion

The *Acacia mearnsii*-based rotational system demonstrates multiple ecological benefits that are central to climate-smart agriculture. This study confirms that the system significantly improves soil properties increasing SOC by up to 83%, available phosphorus by up to 330%, and pH by up to 1 unit. These findings align with Kim et al. (2022), who reported SOC increases of 112–169% and P increases of 687% at charcoal production sites in the same region. Beshir et al. (2025) similarly documented significant increases in SOC, total nitrogen, and available phosphorus in the teff–*Acacia*–charcoal rotation system. The mechanisms include nitrogen fixation, as *A. mearnsii* is a fast-growing nitrogen-fixing tree that enhances soil N availability through root exudation and leaf litter decomposition. Charcoal residues from on-site production add biochar, which increases SOC and black carbon, improves nutrient retention, and raises pH (Kim et al., 2022; Amare et al., 2022). Leaf litter and fine root inputs contribute to soil organic matter, improving soil structure and water holding capacity.

The system contributes to climate change mitigation through carbon sequestration. Kim et al. (2022) reported that converting teff fields to teff–*Acacia* agroforestry over a 12-year period increased SOC stocks by 21 Mg C ha⁻¹ per year. This substantial carbon sequestration potential suggests that the system could contribute to Ethiopia's Nationally Determined Contributions (NDCs) under the Paris Agreement. Additionally, on-site charcoal production, using improved kilns, reduces emissions associated with charcoal production compared to traditional methods (Nigussie & Abele, 2025). Some studies (Nigussie et al., 2021; Worku et al., 2023) have identified trade-offs, including decreased understory vegetation and increased surface runoff as plantations age. Additionally, *Acacia* plantations may reduce streamflow in some areas, though the extent of this impact remains unclear. These trade-offs require careful management through appropriate spacing, rotation timing, and integration with other land uses.

The system provides substantial economic benefits that are critical for poverty reduction and rural livelihoods. The integrated system provides 3.2-fold greater income diversification and 35% lower drought-year income volatility compared to pre-*Acacia* systems. Income diversification is a key indicator of resilience, allowing households to absorb shocks and recover from setbacks (Afework et al., 2024; Nigussie et al., 2021). The revenue multipliers are significant: Teff–*Acacia* intercropping generates 1.3 times more income than sole teff, while fodder–*Acacia* intercropping yields 11 times more than sole fodder (Mekonnen et al., 2023). These multipliers explain why farmers are rapidly converting from monocropping to the *Acacia* system. The high IRR (68%) and BCR (1.62) for the Teff–*Acacia* system indicate that the system is highly profitable. Nigussie et al. (2020) similarly found that the *A. decurrens*-based system had a positive NPV and high IRR, making it financially viable for smallholders. Alemayehu et al. (2026) further confirmed the financial viability of converting agricultural land to plantation forests in Ethiopia. Despite its profitability, the system poses liquidity risks for poor farmers due to the 5-year investment period before charcoal income is realized (Nigussie & Abele, 2025). Access to credit enhances participation by 24.2%, indicating that financial resources are critical for enabling adoption (Mekonnen et al., 2022).

The *Acacia* system has significant social implications that influence its adoption and sustainability. The overall livelihood index increased by 0.24 (from 0.47 to 0.71), representing a substantial improvement in household wellbeing. Financial capital showed the greatest improvement, indicating the system's role in poverty reduction (Afework et al., 2024). The system provides cash income used for education, healthcare, and asset accumulation. The 75% increase in teff yields (1.65 vs. 0.95 t ha⁻¹) during the first rotation year directly enhances household food security. The system also provides fodder for livestock, improving livestock productivity and household nutrition. The system has mixed equity implications. While it provides benefits across households, access to resources (land, credit, training) is often uneven. Nigussie et al. (2021) found that the system may exacerbate inequalities, as wealthier farmers can invest in the system while poor farmers are excluded. Gender-based disparities in access to tree benefits also exist (Afework et al., 2024).

Despite its benefits, the system faces several challenges. Wattle rust disease poses a major threat to *Acacia* plantations, causing substantial tree mortality, reducing charcoal supply and farmer income (Nigussie & Abele, 2025; Tamer et al., 2024). Integrated disease management strategies, including resistant varieties and appropriate tree spacing, are needed. Limited road access, poor market infrastructure, and inadequate government support constrain marketing opportunities (Afework et al., 2024). Producers receive lower returns than traders, and informal fees reduce farmer income. Improved market infrastructure and producer cooperatives could address these constraints. Dense tree planting can reduce infiltration, increase runoff, and decrease understory vegetation (Worku et al., 2023). Negative impacts on water resources require careful management, including appropriate planting densities and integration with other land uses. High production costs, including labor for planting and charcoal production, limit profitability for some farmers. The liquidity constraint (5-year investment period) particularly affects poor farmers who cannot afford long-term investments (Nigussie & Abele, 2025).

The *Acacia* system's rapid expansion and demonstrated benefits suggest that it should be supported through appropriate policies. Key recommendations include providing affordable credit to enable resource-poor farmers to adopt the system, as access to credit enhances participation by 24.2% (Mekonnen et al., 2022). Improving road access, market facilities, and market information systems would enhance market access, while producer cooperatives can enhance bargaining power. Promoting improved charcoal production technologies (kilns) would reduce emissions and health risks, and extension services should include training on sustainable management practices. Developing and disseminating disease-resistant *Acacia* varieties would address pest and disease challenges. Conducting further research on trade-offs, water resources impacts, and system optimization is needed. Long-term monitoring of the system's sustainability is also essential. Addressing gender disparities in access to benefits, supporting women's participation in value-added activities through targeted training and resources, and monitoring food prices and land-use shifts to ensure the system does not undermine food security are also important policy considerations.

Conclusion

The *Acacia mearnsii*-based rotational agroforestry system in the Upper Blue Nile Basin provides substantial evidence of being a climate-smart agricultural practice that contributes to food production, fodder provision, and cash generation while building resilient communities and sustainable livelihoods. Ecologically, the system significantly improves soil properties: SOC increased by up to 83%, available phosphorus by up to 330%, and pH by up to one unit. These improvements are driven by nitrogen fixation, organic matter additions, and charcoal residues. The system contributes to climate change mitigation through carbon sequestration, with potential SOC stock increases of 21 Mg C ha⁻¹ per year. Economically, the system outperforms sole cropping alternatives: Teff–*Acacia* intercropping provides 1.3 times more income than sole teff, while fodder–*Acacia* intercropping generates 11 times more income than sole fodder. The integrated system contributes 82% of household income (ETB 86,352) and reduces income volatility during drought years by 35%. The financial viability is confirmed by high NPV (ETB 38,820 ha⁻¹), BCR (1.62), and IRR (68%). Socially, the system improves household livelihoods: the overall livelihood index increased from 0.47 to 0.71, with financial capital showing the greatest improvement (+ 0.43). Teff yields increase by 75% during the first rotation year, enhancing food security. Adoption follows a locally optimized 4–5 year cycle that provides short-term food, medium-term fodder, and long-term cash income. However, challenges related to pests/diseases, market access, liquidity constraints, and environmental trade-offs require policy attention. To realize the full potential of this system, policymakers should support financial inclusion, market infrastructure development, technology transfer, disease management, and gender equity. The system demonstrates that farmer-driven innovation can deliver climate adaptation, mitigation, and sustainable livelihoods when supported by appropriate institutional frameworks. As the system expands across the Upper Blue Nile Basin, it holds promise for advancing Ethiopia's green growth and climate adaptation goals. Future research should focus on optimizing management practices, monitoring long-term sustainability, and scaling the system to other agro-ecological zones in Ethiopia and similar contexts.

Declarations

Ethics Approval and Consent to Participate

This study was conducted in accordance with the ethical standards of the University of Gondar's Institutional Review Board (IRB). Ethical approval was obtained prior to the commencement of data collection (Protocol Number: UOG/IRB/2024/056). Informed consent was obtained from all participants, who were fully informed about the purpose of the study, the nature of their participation, and their right to withdraw at any time without consequence. The research involved household surveys, focus group discussions, and key informant interviews with human participants; however, no animals or endangered plant species were used in this research. All procedures were performed in compliance with ethical standards for social science research involving human participants. We confirm that all methods were carried out in accordance with relevant institutional and national guidelines and regulations.

Consent for Publication

We understand that the information provided in this manuscript will be published without participant names attached, but that full secrecy cannot be guaranteed. We understand that the text and any pictures published in the article will be freely available on the internet and may be seen by the public. The pictures and text may also appear on other websites or in print, may be translated into other languages, or used for commercial purposes. We have been offered the opportunity to read the article. Informed consent for publication of anonymized data was obtained from all participants, who were made aware that the results would be disseminated through academic publications and presentations. Participants were assured that their identities would remain confidential and that any identifying information would be removed from the data before analysis and publication.

Competing Interests

The authors declare no competing interests. None of the authors have financial or personal relationships with other people or organizations that could inappropriately influence or bias the work reported in this manuscript. The research was conducted independently without any commercial or financial relationships that could be construed as potential conflicts of interest.

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Author Contribution

DFS was responsible for the conceptualization of the research, designing the overall study methodology, leading the data collection efforts, performing data analysis and interpretation of findings, and drafting and revising the manuscript. AAK contributed to data collection, conducted soil analysis, assisted with plot allocation, interpreted soil-related results, and provided manuscript editing and commentary. DFA participated in research design, provided guidance on soil data interpretation, validated laboratory methods, and contributed to manuscript editing and scientific oversight. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request. Due to the sensitive nature of household income data and the promise of confidentiality made to participants, some individual-level data are not publicly available. However, aggregated data and analytical outputs can be shared for academic purposes after approval from the University of Gondar's Institutional Review Board. Requests for data should be directed to the corresponding author at derbabaw.fentie@uog.edu.et. All data requests will be reviewed and fulfilled subject to applicable ethical and privacy considerations.

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Figures



Figure 1

Map of the study area showing Fagita Lekoma District within the Upper Blue Nile Basin, Ethiopia



Figure 2

Acacia system with teff cultivation (a); Acacia system along with grasses (b); matured Acacia plantation (c); Acacia wood harvested for charcoal production (d); and three stages of the Acacia charcoal production process (e-h).

Supplementary Files

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