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MARKET-DRIVEN ACACIA MEARNSII-BASED TANGUAY SYSTEM FOR SUSTAINABLE BIOENERGY PRODUCTION IN THE UPPER BLUE NILE BASIN, ETHIOPIA

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Abstract

As energy demand increases in urban areas of Ethiopia, the expansion of smallholder plantations, particularly Acacia mearnsii woodlots, has become essential in meeting bioenergy needs. However, small-scale farmers have been underrepresented in the value-added bioenergy production systems. This study explores factors influencing value addition and benefit distribution in the market-driven A. mearnsii-based Tanguay system for bioenergy production. A random sample of 148 producers and 52 traders was surveyed using snowball sampling, supplemented by 7 interviews, 6 focus groups, and field observations. The Heckman two-stage model analyzed participation and product volume in the bioenergy market. A. mearnsii woodlots cover 31,000 hectares, producing 145,000 tons of charcoal annually (equivalent to 8.3 million sacks of 17.4 kg), valued at $43 million. These plantations sequester 5.3 million tons of CO_2 and reduce deforestation on 93,000 hectares. Small-scale farmers earn $1,936 annually, accounting for 60% of their income, while traders earn between $5,000 and $30,000. The first-stage probit model revealed that age ($p<0.03$), experience ($p<0.003$), access to credit ($p<0.034$), and contract marketing ($p<0.000$) significantly influenced farmers' decisions to engage in value addition. The second-stage Heckman model revealed that training services ($p < 0.041$), livestock holdings ($p < 0.054$), and age ($p < 0.058$) were key determinants of the volume of bioenergy products for value addition. The total relative commercialization margin was 58%, indicating that marketing actors captured

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a larger share of the final market price, with farmers earning 42%. The study concludes that A. mearnsii woodlots support bioenergy production, income for smallholders, local revenue, job creation, and better rural livelihoods. Improving market access, forming cooperatives, and providing technical training are keys to achieving equity and sustainability in bioenergy production in Ethiopia.

Keywords: ***Acacia, bioenergy, commercialization, income, market access, policy, smallholder planta-tions***

I. INTRODUCTION

Ethiopia's growing urban energy demand has increased the need for sustainable bioenergy production [1]. Charcoal, derived from biomass, plays an essential role in meeting this demand and has become a critical energy source for households and small enterprises [2]. The development of smallholder woodlots has emerged as a reliable system for the production of charcoal and firewood [3]. Among various species used in these systems, *Acacia mearnsii* (Black Wattle) has gained prominence due to its fast growth, adaptability, and high biomass yield, making it an ideal species for bioenergy production [4]. In the Upper Blue Nile Basin, smallholder farmers have increasingly adopted *Acacia mearnsii*, marking a significant shift from traditional agriculture to tree-based bioenergy systems [3, 5].

Deforestation and land degradation are serious challenges in Ethiopia's highlands, compounded by factors such as soil erosion, overgrazing, and unsustainable farming practices [6, 7]. To address these issues, many smallholder farmers in the region have adopted the *Acacia mearnsii*-based Taungya system, which integrates tree planting with agriculture. This agroforestry approach mitigates land degradation while enhancing economic outcomes by providing an additional source of income from charcoal production [2, 3].

Despite *Acacia mearnsii's* suitability for bioenergy production in Ethiopia, its full potential remains largely untapped due to limited engagement in value-added activities [4]. Most farmers primarily focus on basic biomass extraction, such as cutting wood for charcoal, without venturing into processing or marketing, which restricts their ability to realize the full economic benefits [5].

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This lack of value addition hinders the development of a sustainable bioenergy market and limits opportunities for improved livelihoods [8].

As the demand for bioenergy continues to rise, establishing a comprehensive value chain that encompasses the production, processing, and marketing of value-added products is crucial for the long-term sustainability of bioenergy systems [9]. Research on the distribution of benefits within the *Acacia mearnsii* woodlot value chain is limited, especially regarding the role of value addition in improving livelihoods [8]. This study aims to explore the potential of value addition and the roles of smallholder farmers in bioenergy production, processing, and marketing. Ultimately, it seeks to unlock the full potential of *A. mearnsii* for sustainable bioenergy production and enhanced livelihoods in the Upper Blue Nile Basin and beyond.

II. MATERIALS AND METHODS

A. Study site

This study was carried out in the Upper Blue Nile Basin, located in the northwestern highlands of Ethiopia, a region that has become a prominent hub for *Acacia mearnsii*-based woodlot production. This trend has been largely driven by the growing demand for bioenergy, particularly charcoal and fuelwood. Geographically, the study area is situated between 10°57'23" to 11°11'21" N latitude and 36°40'01" to 37°05'21" E longitude, encompassing approximately 741 hectares. It lies at high altitudes ranging from 1,800 to 2,900 meters above sea level—with some areas reaching up to 3,200 m.a.s.l.—and is characterized by vegetation ranging from moist subtropical to cool highland climate. The region receives annual rainfall between 1,500 mm and over 2,000 mm, with mean annual temperatures ranging from 15°C to 24°C. These are conditions that favor the cultivation of fast-growing tree species like *Acacia mearnsii*. Introduced approximately more than 20 years ago, *A. mearnsii* is commonly grown using the Taungya agroforestry system, which combines tree planting with seasonal crop cultivation, helping to restore degraded lands while supporting local livelihoods.

The landscape was previously known for severe land degradation, acidic and nutrient-poor soils, high erosion risk, and chronic dependence on food aid, which collectively contributed to net emigration from the area. However, the introduction of *A. mearnsii* plantations has significantly

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altered land use dynamics, contributing to both ecological restoration and economic development. The region now hosts a rich mix of native and exotic tree species. Common native species include *Acacia abyssinica, Albizia gummifera, Croton macrostachyus, Combretum molle, Cordia africana, Schefflera abyssinica, Dovyalis abyssinica, and Entada abyssinica.* In forest remnants, species such as *Bersama abyssinica, Calpurnia aurea, Olea europaea,* and *Ficus thonningii* are frequently observed. Among exotic species, *Acacia mearnsii* and *Eucalyptus camaldulensis* are widely cultivated in woodlots due to their high biomass yield and economic importance. These efforts have played a pivotal role in reducing pressure on natural forests, enhancing soil fertility, and promoting sustainable land use across the degraded highlands of the Upper Blue Nile Basin.

B. Sampling technique and sample size determination

A multi-stage stratified random sampling technique was applied to identify representative households for the study. The Upper Blue Nile Basin was purposely selected due to its high potential for *A. mearnsii* woodlot production, particularly for charcoal and fuelwood. Its favorable altitude, rainfall, and soil conditions have made it a major area for bioenergy development. Three kebeles are known for active *A. mearnsii* cultivation was chosen. Before the main survey, a pre-test was carried out from December to March 2020 using 15 questionnaires to refine the data collection process. From the household list, 148 producers were randomly selected, and the sample size was determined using Cohen's formula to ensure reliable and representative findings.

$$n = \left(\frac{(Z_{\alpha/2} + Z_{\beta})^2 \cdot 2 \cdot \sigma^2}{\Delta^2} \right)$$

- n = sample size **per group**
- $Z_{\alpha/2}$ = z-score for the desired **confidence level** (e.g., 1.96 for 95%)
- Z_{β} = z-score for desired **power** (e.g., 0.84 for 80% power)
- σ = **standard deviation** (assumed or from pilot data)
- Δ = **minimum detectable difference** (effect size)

C. Data collection methods

Data were gathered using a mix of household surveys, interviews, FGDs, and field observation. A total of 148 producers (n=148) were randomly surveyed. Semi-structured interviews (n=52) were

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done with key actors: intermediaries (10), brokers (8), local collectors (12), wholesalers (9), and retailers (13), identified through snowball sampling. Six FGDs (n=6) were conducted with community elders, producers' group leaders, and residents to understand charcoal production and trade dynamics. Seven key informant interviews (n=7) were also held with agriculture experts, kebele leaders, and traders. Field observations helped cross-check the information collected.

D. Data analysis methods

The collected data were analyzed using various descriptive statistics and econometric techniques. Data analysis involved descriptive statistics (means, percentages, standard deviations) to summarize socio-economic and production data. Market analysis assessed price differentials through the relative commercialization margin. Econometric modeling used Probit regression to analyze adoption likelihood and Heckman's two-stage model to identify biomass production determinants for value addition. In the first stage, Probit regression examined factors influencing participation, and in the second stage, OLS regression analyzed participation levels, correcting bias using the Inverse Mill's Ratio (IMR). The participation equation is:

$$Y_i = \chi_i \beta_i + \epsilon_i, \quad \epsilon_i \sim N(0,1)$$

In the second stage:

$$Y_i = \beta_i \chi_i + \lambda_i \mu_i + \epsilon_i, \quad \epsilon_i \sim N(0, \delta^2)$$

Where Y_i indicates participation, and λ_i is the IMR, calculated as:

$$\lambda_i = \frac{\phi(\chi_i \beta_i)}{1 - F(\chi_i \beta_i)}$$

III. RESULTS

A. Sustainable bioenergy production of *Acacia mearnsii*-based Tanguay system

The market-driven *Acacia mearnsii*-based Tanguay system in the Upper Blue Nile Basin is a sustainable bioenergy production model that combines agroforestry, crop cultivation, livestock fodder, and charcoal production. This 4–5 years rotational system starts by planting teff (Eragrostis tef) alongside young *A. mearnsii* seedlings in the first year. The teff provides immediate income and food security, while the *A. mearnsii* seedlings begin to grow. By the second year, fodder

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grasses are planted between the rows of *A. mearnsii*, supporting livestock feed and increasing the land's productivity. The system benefits from improved soil fertility, moisture retention, and microclimatic conditions, which can increase crop yields by 2 to 4 times compared to monocropping. These environmental improvements contribute to higher farm outputs and enhanced resilience against climate impacts.

As the *A. mearnsii* trees mature in the third to fourth year, they enrich the soil through nitrogen fixation and stabilize the land. By the fourth or fifth year, the trees are harvested, and charcoal production is carried out on-site using traditional earth mound kilns. This charcoal is sold to local and urban markets, providing farmers with a source of income. After the harvest, the land is replanted at the onset of the rainy season, restarting the rotation cycle. The Tanguay system incorporates indigenous knowledge, such as the teff–*A. mearansi*–charcoal rotation, a climate-smart agricultural technology that integrates food, fuel, and fodder within a sustainable land-use model. By combining indigenous practices with market-driven strategies, the system not only generates bioenergy but also addresses land degradation, energy scarcity, and rural poverty in the Upper Blue Nile Basin. This approach supports climate resilience, sustainable livelihoods, and contributes to Ethiopia's green growth and climate adaptation goals.

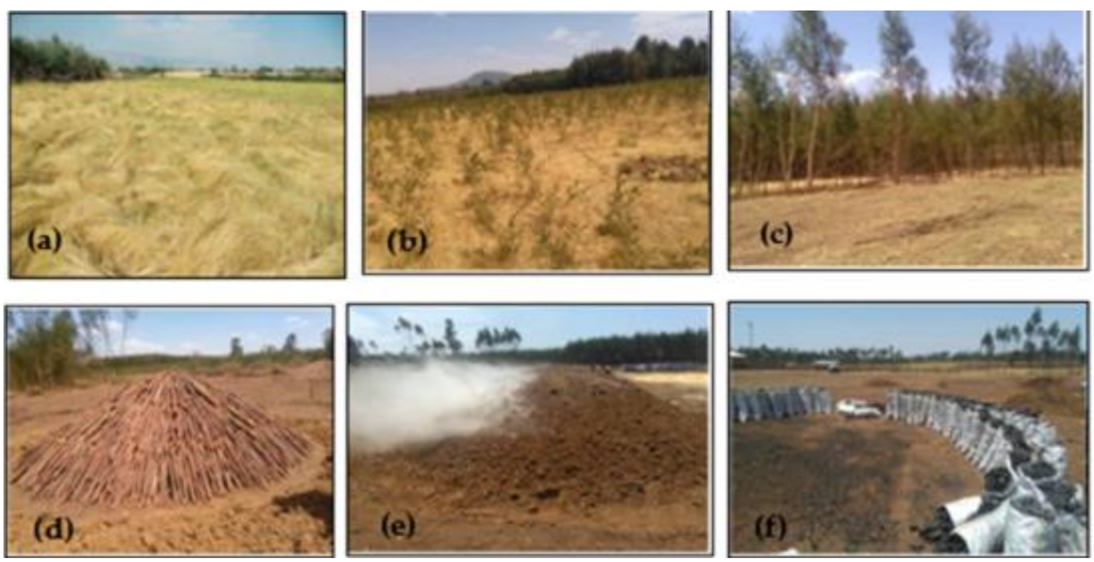

Fig.1. The photographs, adopted from Miftha Beshir, depict: (a) the teff monocropping system; (b) the teff–*Acacia mearnsii*–charcoal production (TACP) rotation system; (c) *A. mearnsii* seedlings planted with teff, showing *A. mearnsii* at the tree stage; (d) piles of *A. mearnsii* wood; (e) a charcoal production kiln; and (f) the harvesting of charcoal in the TACP system.

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B. Revenue distribution, equity, and value added along the *A. mearnsii* bioenergy market

The results show various fees imposed on *A. mearnsii* woodlot products throughout the value chain in the Upper Blue Nile Basin. Skilled local workers are paid a charcoal-making fee of $3.13 per quintal, while daily labor costs $4.00 per day for local workers. Transport fees depend on distance, with charges ranging from $0.937 for local transport to $5.00 for transporting to urban markets.

Brokers earn $0.313 per quintal, and cooperative members receive fees for loading/unloading and stripping, both valued at $0.937 and $0.313, respectively. Additionally, the regional government receives a royalty fee of $2.34, while local government collects a locality fee of $0.457 and a sport/infrastructure fee of $0.156, indicating the diverse roles and financial contributions of both local workers and governmental bodies within the bioenergy production.

TABLE I: Local duties and workers' fees imposed on *a. Mearnsii* woodlot products

Fee	**Amount (USD/quintal)**	**Beneficiaries**	**Remarks**
Charcoal Making Fee	3.13	Skilled local workers	
Daily Labor Fee	4.00/day	Local workers	
Transport to Nearest Road	0.937	Local workers	Depends on distance
Brokerage Fee	0.313	Brokers	3.13/Ql, informal
Transport to Urban Market	5.00	Owners of the trucks	Depends on distance
Loading and Unloading Fee	0.937	Cooperative members	
Striping Fee	0.313	Cooperative members	
Royalty Fee	2.34	Regional government	
Locality Fee	0.457	Local government	
Sport/Infrastructure Fee	0.156	Local government	

The results provide a comprehensive evaluation of the market-driven *A. mearnsii*-based Tanguay system for bioenergy production in the Upper Blue Nile Basin, Ethiopia, highlighting its potential to drive sustainable bioenergy production and economic growth via the charcoal value chain. Each actor in the value chain—producers, local intermediaries, wholesalers, and retailers—plays a crucial role in converting *A. mearnsii* biomass into an economically viable energy source. The

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analysis of net income, income per ton, profit margin, and volume handled provides valuable insights into each stage's contribution to the system's success.

Producers handle 34,050.72 tons of charcoal annually, earning a net income of $1,935.85 with an income per ton of $0.06. The 38% profit margin suggests efficient management of operational costs despite the labor-intensive nature of charcoal production. Local intermediaries, including collectors and brokers, manage 250,257.60 tons of charcoal annually, earning $6,040.65, with an income per ton of $0.02 and a 12.3% profit margin. Their role is crucial in linking production with regional markets.

TABLE II: Revenue distribution, value addition, and profit margins across *a. Mearnsii* wood

Actor	Volume Handled (Ton/Year)	Average Cost (USD/Ton)	Gross Revenue (USD)	Total Cost (USD)	Net Income (USD/Year	Value Added (USD/Ton)	Profit Margin (%)
Producers	34,051	92	85,143	56,022	1,936	58	38
Intermediaries	250,258	119	1,137,321	1,018,426	6,041	24	12
Wholesalers	696,984	129	1,062,587	897,122	30,188	43	17
Retailers	22,412	246	7,729	5,512	2,119	53	28
Total	1,003,705	-	2,292,780	1,976,082	40,284	-	-

NB: the volume in tons per year, assuming each sack weighs 17.4 kg

Wholesalers manage 696,984 tons of charcoal annually, earning a net income of $30,188.07, with an income per ton of $0.04 and a 17.2% profit margin. Their larger volume of transactions allows for higher profitability, connecting regional markets to retail distribution. Retailers handle 22,411.60 tons of charcoal, earning $2,119.29 with an income per ton of $0.09 and a 27.5% profit margin. They provide value through packaging, marketing, and direct sales, capturing a larger share of the profit.

Aggregating all actors, the system handles 1,003,704.92 tons of charcoal annually, generating a total net income of $40,283.86, with an average income per ton of $0.04. The results indicate significant economic benefits, with profit margins reflecting varying levels of value-added processes, especially higher margins for retailers and wholesalers.

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The market-driven *A mearnsii*-based Tanguay system in the Upper Blue Nile Basin offers a robust model for sustainable bioenergy production. The system involves the integration of *A. mearnsii* plantations, crop cultivation, and charcoal production, creating a multi-functional agroforestry approach. The biomass yield across the three sites (A, B, and C) in the basin ranges from 87.3 tons per hectare at Site A to 97.5 tons per hectare at Site C. On average, the biomass yield across all sites is 93.4 tons per hectare, highlighting the system's potential to generate substantial bioenergy resources.

The total biomass produced is consistent at 578,080 tons across all three sites, ensuring a steady supply for charcoal production. The system generates 145,000 tons of charcoal annually, which equates to 8.3 million sacks of charcoal, each weighing 17.4 kg. This volume of production plays a crucial role in meeting the regional demand, with 85% of sales targeting Addis Ababa and 15% directed to other regional cities. The conversion efficiency of the system stands at 25%, meaning that 25% of the biomass produced is converted into charcoal, which aligns with typical conversion rates using traditional earth mound kilns.

TABLE III: Summary of woodlot and land use dynamics in the upper blue Nile basin

Parameter	**Site A**	**Site B**	**Site C**	**Overall Value**
BiomassYield (tons/ha)	87.30	95.40	97.50	93.4
Total Biomass (tons)	578,080	578,080	578,080	578,080
Charcoal Production (tons)	145,000	145,000	145,000	145,000
Charcoal Production (sacks)	8.3 million	8.3 million	8.3 million	8.3 million
Conversion Efficiency (%)	25%	25%	25%	25%
Land Use Change (%)	42.1% *A. mearnsii*, 30% Cropland	42.1% *A. mearnsii*, 30% Cropland	42.1% *A. mearnsii*, 30% Cropland	42.1% *A. mearnsii*, 30% Cropland
Carbon Sequestration (tons CO_2/ha/yr)	5-10 tons	5-10 tons	5-10 tons	7.5 million tons (avg)
Income Increase (%)	75% (Charcoal Producers)	75% (Charcoal Producers)	75% (Charcoal Producers)	75% (Charcoal Producers)

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Net Income per Sack (USD)	\$0.62	\$0.62	\$0.62	\$0.62
Total Charcoal Income (USD)	\$5,140,000	\$5,140,000	\$5,140,000	\$15,420,000

In terms of land use change, the system employs 42.1% *A. mearnsii* plantations and 30% cropland across all sites. This combination supports both bioenergy production and food security, as crops like teff are cultivated alongside the *A mearnsii* trees. The system's contribution to carbon sequestration is significant, with an estimated 5 to 10 tons of CO_2 sequestered per hectare per year. In total, the plantations sequester approximately 7.5 million tons of CO_2 annually, offering both climate resilience and improved soil health.

C. Econometric Results

1) *Determinants of household participation in Acacia mearnsii-based value addition for sustainable bioenergy production*: A Heckman two-step selection model was employed to analyze factors influencing household participation in *Acacia mearnsii* woodlot product value addition for sustainable bioenergy production. The market-driven *A. mearnsii*-based Tanguay system for bioenergy production in the Upper Blue Nile Basin is influenced by key factors affecting participation and value addition. Post-estimation of the selection equation was conducted to derive marginal effects, which provide meaningful interpretation of variable impacts [10]. Among the twelve variables included in the model, four were statistically significant: age of the household head ($p = 0.030$), household experience in woodlot management ($p = 0.003$), access to credit services ($p = 0.034$), and engagement in contractual agreements ($p = 0.000$).

The age of the woodlot producer household head was found to be statistically significant at the 5% probability level, with a negative sign, indicating that each additional year of age decreases the likelihood of participation in *A.* mearnsii *w*oodlot product value addition by 0.8% ($p = 0.03$) (Table IV). This negative relationship may be explained by the labor-intensive nature of woodlot product processing, which can discourage older producers from participating. Additionally, older household heads may be more risk-averse and less willing to adopt new technologies such as improved kilns for processing *A.* mearns*ii* products. This finding aligns with [11], who reported that older woodlot producers are less likely to engage in charcoal production due to labor

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constraints. Similarly, [12] noted that older individuals are generally less receptive to innovation and more cautious in adopting new practices compared to younger people. Conversely, the experience of the woodlot producer household head was significant at the 1% probability level with a positive sign, indicating that each additional year of experience increases the likelihood of participation in *A. mearnsii* woodlot product value addition for bioenergy production by 8.5% (p = 0.003) (Table IV). This suggests that more experienced producers are more likely to engage in activities such as converting standing woodlots into charcoal. Experienced households tend to understand the benefits of processing and are more skilled in using value-added techniques. This finding is supported by [13] who observed that experienced coffee farmers are more likely to adopt processing practices such as drying, which add value to the product. Similarly, experienced *A. mearnsii* producers are better equipped to handle production and processing technologies effectively.

Access to credit had a positive and significant influence on participation in *A. mearnsii* woodlot product value addition (p = 0.034). This implies that, other factors being constant, participation increased by 24.2% for households with credit access. This shows that credit helps woodlot producers improve their financial capacity to invest in key activities such as seedling preparation, planting, tree felling, disbranching, cross-cutting, charcoal production, and transportation. With improved access to finance, producers can afford better inputs and tools, making it easier to engage in processing activities. This result supports the findings of [1]].w ho reported that credit access boosts farmers' ability to purchase inputs and enhances participation in value-added activities.

Contractual agreements of household heads in woodlot production were found to be highly significant but hurt participation in value addition (p = 0.000). Specifically, each additional contractual agreement reduced the probability of participation in *A. mearnsii* woodlot value addition by 60.8%, holding other factors constant. This negative relationship may be explained by producers entering contracts to sell their plantations or *A. mearnsii* woodlots before harvesting or sharing their woodlots, which reduces their involvement in value-added activities. Additionally, advance payments tied to contracts might encourage producers to sell their woodlots early, sometimes even before full maturity, to benefit from rising woodlot prices.

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TABLE IV: The heckman two-step selection equation result

Variables	dy/dx	Std. Err.	Z	P>|z|
Sex of household head	0.06706	0.17116	0.39	0.695
Age of household head	-0.0081	0.00377	-2.17	0.030**
Educational level	0.14505	0.10263	1.41	0.158
Adult equivalent size	-0.0440	0.03889	-1.13	0.258
Woodlot size	0.08166	0.06951	1.17	0.240
Tropical Livestock Unit	-0.0195	0.01763	-1.11	0.268
Distance to market	-0.0975	0.12045	-0.81	0.418
Household experience	0.08598	0.02888	2.98	0.003***
Market information access	0.17764	0.11825	1.50	0.133
Credit access	0.24224	0.11449	2.12	0.034**
Contractual agreement	-0.60777	0.11657	-5.21	0.000***
Training access	0.01656	0.11649	0.14	0.887

***, ** and * are statically significant at 1%, 5% and 10% significance level respectively

2) *Factors Influencing the Volume of Participation in Value-Added Acacia mearnsii Woodlot Products for Bioenergy Production*: Factors influencing the volume of participation in value-added *Acacia mearnsii* woodlot products for bioenergy production were analyzed using OLS regression in the second stage of the Heckman two-step outcome equation. The results indicate that the volume of participation is significantly affected by the household head's age (p = 0.058), livestock holdings (p = 0.054), and access to training services (p = 0.041) (Table IV). Notably, the coefficient of the Inverse Mills' ratio (Lambda) is positive and statistically significant at the 10% level (p = 0.053), suggesting the presence of sample selection bias [14].This means that unobservable producer characteristics influence woodlot producers' decisions to participate in value addition, which in turn affects the volume of value-added products. Overall, younger household heads, larger livestock holdings, and better access to training are associated with increased participation volume in value-added *A. mearnsii* woodlot products for bioenergy production.

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The age of the Acacia mearnsii woodlot producer household head significantly affects the volume of participation in value-added products at the 10% significance level (p = 0.058), with a negative relationship. Specifically, for each additional year in age, the volume of value-added products decreases by 709.70 ETB. This suggests that younger producers are more energetic and actively engaged in the labor-intensive production and marketing processes, while older producers tend to reduce their participation due to decreased physical capacity. These findings are consistent with previous studies [15],[19],[20] indicating that older farmers often switch to less labor-intensive activities or rent out their land. Similarly,[21] reported a negative impact of household head age on the volume of value-added milk products, supporting the conclusion that younger producers contribute more to value addition in labor-intensive sectors. Livestock holdings, expressed in Tropical Livestock Units (TLU), showed a significant positive effect on the volume of participation in value-added bioenergy products at the 10% significance level (p = 0.054). Specifically, an increase of one TLU raises participation volume by 2,630.3 ETB, holding other factors constant. This indicates that livestock ownership provides essential cash income for rural woodlot producers, enabling them to purchase necessary inputs such as seedlings, nylon bags, and plastic tubes, and to finance value-adding activities including charcoal transportation from production areas to nearby roads or markets. These findings align with Tadie[21], who reported that farmers with larger livestock holdings tend to generate cash through sales, facilitating farm input purchases and meeting household needs. Livestock thus plays a key role in supporting participation in *A. mearnsii* woodlot product value addition for bioenergy production.

Access to training services has a significant and positive impact on the volume of participation in value-added *Acacia mearnsii* woodlot products for bioenergy production. The results show that those who received training increased their participation by 20,297.55 ETB (p = 0.041). This highlights the importance of training in providing producers with the necessary skills and knowledge to improve their production and marketing practices. Well-informed producers are better equipped to adopt effective techniques, which ultimately enhances their productivity and ability to compete in bioenergy markets.

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TABLE IV:The HECKMAN two-step outcome equation result

Variables	Coef.	Std.Err.	Z	P|>z|
Sex of household head	14713.61	17312.48	0.85	0.395
Age of household head	-709.702	373.73	-1.90	0.058*
Educational level	14971.24	9359.9	1.60	0.11
Adult equivalent family size	3181.62	3344.14	0.95	0.341
Tropical Livestock Unit	2630.27	1364.85	1.93	0.054*
Household experience	13479.74	11122.04	1.21	0.226
Market information access	-2333.87	11698.07	-0.20	0.842
Credit access	3526.67	10920.86	0.32	0.747
Contractual agreement participation	-17449.38	14934.4	-1.17	0.243
Training access	20297.55	9920.992	2.05	0.041**
CONST	16529.47	33012.76	0.50	0.617
Mill Lambda (IMR)	32314.91	16707.99	1.93	0.053*
Rho	0.88043			
Sigma	36703.72			

*, ** *** *indicate significant difference at 10%, 5% and 1% probability level respectively*

IV. DISCUSSIONS

Charcoal production under the *A. mearnsii*-based Tanguay system provides substantial income across the value chain, though earnings are uneven. Producers, managing 34,050.72 tons/year, earn the lowest unit income (USD 0.06/ton) despite performing the critical task of biomass conversion. In contrast, wholesalers and retailers earn USD 0.04 and USD 0.09/ton, respectively, benefiting from market access, storage, and urban proximity [14]. Intermediaries, managing 250,257.60 tons/year, earn only USD 0.02/ton, reflecting minimal value addition [14]. The overall district-level value addition reaches USD 27.5 million annually, highlighting the system's economic potential, although income disparity calls for intervention. Recommended measures include direct market access, technology efficiency, and producer cooperatives [16].

Biomass yield ranges from 87.30 to 97.50 tons/ha, aligning with comparable bioenergy systems [17]. Total site yield stands at 578,080 tons, confirming *A. mearnsii* as a dependable energy source.

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A conversion efficiency of 25% falls within global norms (20–30%), depending on moisture content and kiln efficiency [18]. Land use change trends show reduction in cropland (from 67% to 30%) and grazing land (from 19% to 12%), with a rise in Acacia woodlots (42.1%), indicating land restoration benefits [19]. The species supports soil fertility and erosion control, promoting sustainable land use [18].

The system boosts producer income by 75%, contributing to livelihood improvement and poverty reduction goals [21]. Its adaptability across Ethiopia and Zambia suggests suitability for broader regional adoption [19]. Household attributes influence engagement in value-added roles. Age negatively correlates with participation, as older farmers tend to avoid labor-intensive processes [20]. In contrast, experience positively influences involvement, indicating the value of skills and know-how [18].

Access to credit enhances participation by 24.2%, demonstrating the importance of financial resources for scaling value chains [19]. However, contractual engagement reduces participation by 60.8%, implying that restrictive conditions deter flexibility [21]. Livestock assets serve as liquidity sources for inputs and transport, further supporting engagement. Training exposure significantly increases value addition, underlining the need for capacity development [20]. The Heckman model affirms the presence of latent factors influencing participation decisions, highlighting the need for further inquiry [21].

V. CONCLUSIONS AND RECOMMENDATION

The *Acacia mearnsii*-based bioenergy system in the Upper Blue Nile Basin provides essential economic support to rural communities, yet income disparities persist along the value chain. Producers, despite their crucial role, receive the lowest financial returns, while wholesalers and retailers capture larger profits. Addressing these disparities requires policy interventions to empower producers, improve market access, and ensure fair pricing.

To enhance sustainability, strengthening producers' bargaining power through cooperative organizations and direct market access is key. Adopting modern charcoal production technologies and sustainable harvesting practices will boost efficiency and reduce environmental degradation. Establishing a structured market with clear regulations can prevent price exploitation, while promoting responsible consumption through consumer awareness supports ethical behavior. The

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success of the system depends on fostering collaboration among stakeholders, including government, research organizations, and private enterprises. Policymakers should integrate economic incentives with environmental goals. Targeting younger producers and improving access to training, livestock, and credit will enhance participation in value-added activities. Expanding this bioenergy system, optimizing conversion technologies, and promoting its adoption across Ethiopia and sub-Saharan Africa will provide significant economic and environmental benefits.

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