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Exploring Socio-Economic Characteristics on Adoption Intensity of Biochar Among Farming Households in Sub-Humid Regions of Western Kenya

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Agriculture is a cornerstone of Kenya's economy, yet declining soil fertility and low adoption of sustainable agricultural technologies, such as biochar, have hindered productivity among smallholder farmers. Biochar is perceived to be a cost-effective technology especially among resource constraint farming households. Despite many smallholder farmers acknowledging the importance of biochar as a soil amendment, most farmers face socio-economic barriers that hinder its adoption at scale. This study focused on how socio-economic factors influence adoption intensity of biochar, with a focus on the farming households in the sub-humid regions of Western Kenya. Employing a multistage stratified sampling procedure and Heckman selection model, the study reveals that awareness of biochar, access to credits, total land used in farming and education level positively and significantly influences adoption of biochar while total land owned in acres negatively and significantly influences adoption of biochar. Similarly, awareness of biochar, access to credits, and education level positively and significantly influences adoption intensity of biochar while terms of land ownership negatively and significantly influence adoption intensity of biochar. The study identifies awareness of biochar, education, credit access, and land ownership as key factors influencing its adoption by smallholder farmers. Promoting biochar as a soil amendment and carbon sequestration technique for farmers should be the main goal of the government, non-governmental organizations, and development organizations. Promoting the advantages of biochar for crop yields and soil fertility should be spearheaded by the Ministry of Agriculture's Extension Department. While development organizations offer financial assistance and training to promote adoption, policymakers should push farmer cooperatives to reduce the cost of biochar production and implementation.

Keywords: Soil bulk density, microbial biomass carbon, inverse mills ratio, marginal effect, robust standard error.

INTRODUCTION

Agriculture is the backbone of Kenya's economy, and increasing agricultural productivity is seen as a key strategy for reducing poverty among smallholder households (Wanzala *et al.,* 2024). As part of its economic pillar, Kenya's Vision 2030 seeks to promote the agricultural sector, which has faced several challenges, including declining soil productivity (Evans *et al.,* 2021). This has been caused by overreliance on conventional methods of farming by many smallholder farmers (Ndegwa *et al.,* 2023). Biochar therefore aims to address this declining soil productivity and low agricultural productivity among smallholder farmers, driven by overreliance on conventional farming practices, which has led to the depletion of soil fertility. Intensity of adoption of biochar application and other sustainable agricultural technologies which can result in soil amendment and improvement is still very low among many smallholder farmers (Kiprotich *et al.,* 2024).While farmers have recognized the benefits of biochar as a soil amendment, most of the farmers' propensity to adopt this technology is low due to a number of socio economic barriers and limitations in

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extension services. Moreover, for farmers who have adopted biochar application, the intensity of its use remains quite low. Biochar is a carbon-rich material used as a soil amendment, created by heating organic matter in a low-oxygen environment (Li and Tasnady, 2023). Its application in agricultural soils offers multiple benefits, such as remediating acidic soils which have depleted carbon, as well as increasing soil carbon sequestration, as a result, contributing to climate change mitigation (Rogers *et al.*, 2022). Further, research has shown that biochar enhances soil properties significantly, for instance, it leads to an increase of 64.3, 84.3, 20.1, and 22.9% for total carbon, organic carbon, microbial biomass carbon, and labile carbon respectively (Chagas *et al.*, 2022). This implies that biochar improves carbon sequestration in the soil. Additionally, Wang *et al*. (2024), reported that biochar increases soil cation exchange capacity by 17% which implies that it can improve the soil's ability to retain and exchange essential nutrients like potassium, calcium, and magnesium . Research findings show that application of biochar to the soil also reduces bulk density by 12%, increases soil porosity by 12%, reduces soil Ph. because it is alkaline in nature and decreases soil nitrogen from leaching by up to 20% (Kamali *et al.*, 2022). All this implies that biochar is an effective soil amendment and can be used to increase soil productivity especially in less productive soils.

Adoption of biochar application for soil amendment can be a promising solution to the decreasing agricultural productivity and increasing poverty levels among many smallholder farming households (Shittu *et al.*, 2021). Particularly, soil amendment through biochar application has received substantial attention in the last decade Nogués *et al*. (2023), because of its sustainability. For instance, carbon farming has been proposed as a sustainable way of amending the soil (Sharma *et al.*, 2021). This is because it focuses on supporting farmers to implement sustainable and eco-friendly farming practices. However, despite its benefits, adoption of agricultural technologies such as biochar application for soil amendment in Kenya has been low as a result of the influence of socio-economic barriers. These factors include farmers' age, gender and educational status.

There is substantial literature on biochar, where more focus is on its agronomic benefits, while relatively little is known about the influence of socioeconomic factors on adoption and intensity of adoption of biochar (Rogers *et al.*, 2022). This is a very crucial factor to consider so as to realize the full potential of biochar among smallholder farming households. This gap is notable in the context of farming households in Western Kenya. This study aimed to explore how socio-economic factors such as farmers' level of education, awareness, age, and gender affect the adoption and intensity of biochar use, and to identify strategies for overcoming socio-economic barriers to increase its uptake and effectiveness as a sustainable agricultural practice.

***Literature review*:** Socioeconomic factors that influence degree of adopting biochar include the age of the farmer, educational level, sex, farm size, gender of the farmer and marital status (Colclasure *et al.*, 2024). A report by Beshir *et al*. (2022), showed that if the age of the head of the household increases, adoption of agricultural technologies increases by 1%, implying that old farmers are more knowledgeable on these technologies, have more experience, and have built wide social capital which can provide information about agricultural technologies. However, research carried out by Soriano *et al*. (2024), showed that farmers old farmers had low production of biochar because they face numerous economic constraints and poor health, which hinders their participation in biochar-related activities.

Higher level of education has been found to increase adoption of agricultural technologies (Adams *et al.*, 2024). Farmers with low education levels have less likelihood of adopting modern agricultural technologies Zhou *et al*. (2024), because these technologies need planning and documentation skills which they may not have due to limited access of information as a result of spending few years of learning (Li *et al.*, 2023). A report by Kassa and Abdi (2022), revealed that, only 8.92% of the total respondents who had adopted climate smart agricultural technologies (CSA), were uneducated, meaning that education provided sufficient knowledge on importance, adoption of, and use of CSA technologies to most farmers.

A study done by Yue *et al*. (2023), demonstrated that gender of the household age affects adoption of precision pesticide technologies. A report by Neway and Zegeye (2022), revealed that in households which were headed by males, adoption rate of agricultural technologies was 87.3% compared to households headed by females where adoption rate was 61.2%. This is because males typically hold greater decision-making authority, especially in matters related to agriculture (Ram *et al.*, 2023). Female-headed households may face more constraints when making decisions about adopting technologies, especially when the community or family structures do not fully recognize women as primary agricultural decision-makers. This study however was not in line with the study carried out by Aryal *et al*. (2020), who demonstrated that, in households where women were allowed to make decisions on CSA adoption technologies, adoption prospects of CSA practices increased by 11.80% in comparison to households where decisions related to adoption of CSA technologies were made by men. This implied that women are more focused on ensuring household food security, and hence their likelihood of adopting agricultural technologies is higher.

Findings by Sanogo *et al*. (2023), revealed that marital status positively and significantly influenced adoption of CSA technologies, where, married individuals had a higher likelihood of adopting agricultural technologies. This study was in line with the report provided by Olayemi and Oduntan (2021), where, 64.17% of the small-scale farmers who had adopted improved cassava production technologies were married. This can be attributed to the fact that married individuals tend to have more stable households, which allows for long-term planning and investments in agricultural technologies. Unmarried individuals, especially if they are young, may be more transient or have other priorities, making them less likely to adopt long-term agricultural solutions.

Several studies have also demonstrated that the size of the farmland influences adoption of agricultural technologies. Based on the studies carried out by Wiréhn (2024), farmland size positively affected intensity of CSA technologies adoption, suggesting that farming households that have enormous farmlands had a higher likelihood of adopting CSA technologies. This outcome aligns with that of Kom *et al.* (2022), who reported that land subdivision hindered adoption of CSA technologies, implying that farmers who have small farm holdings are less likely to adopt agricultural technologies as compared to farmers with enormous lands because the financial benefits of adopting new agricultural technologies are often greater for larger farms. The studies do not however explore fully the influence of socioeconomic factors on adoption intensity of biochar. This study aimed to fill this gap by evaluating the influence of socioeconomic factors on uptake intensity of biochar by farmers in the sub-humid regions of Western Kenya for soil health improvement and amendment.

***Theoretical framework*:** This study was anchored on two major theories. Diffusion of Innovation (DOI) theory explains the process by which ideas and practices disseminate within a social system. The theory of DOI was to explore how knowledge on biochar and practices spread among farming communities in Siaya County, following the five main stages of adoption which are awareness, interest, trial, evaluation, and finally adoption. This theory has been applied in identifying factors affecting adoption decision of innovations. DOI suggests that an innovation can be adopted or rejected based on its relative advantages, complexity, and compatibility. DOI has been used by Lee (2024), to explain the development of agritourism in the green tea farms of the northern mountains of Vietnam.

The theory of Planned Behaviour postulates that one's behavior is determined by attitude, subjective norms, and behavioral control (La Barbera and Ajzen, 2024). This theory was used to assess farmer's attitudes toward adoption of biochar, identify the social norms that affect biochar adoption, and monitor farmer's intensity of biochar adoption to examine if their intentions are concurrent with their actual adoption behavior. This theory has been used to predict behavior change, especially technology-related behavior. The theory has been applied to model the intention and behavior of tomato growers in pesticide exposure in Western Iran (Pirmoghni *et al.*, 2024).

MATERIALS AND METHODS

***Description of the study area*:** The study was carried out in sub-humid regions of Western Kenya, specifically Siaya County. This study area was chosen due to its high potential for sugarcane and rice production, providing an abundant feedstock for biochar production. Additionally, some farmers in this region have integrated biochar into their farming practices, although adoption of biochar among farmers is low, and the region faces land and soil degradation. Siaya County borders Kakamega, Busia, Kisumu, and Vihiga Counties. Siaya County is found between latitude 26′ S to 18′ N and longitude 58′ E and 33′ W. It has six sub-counties, which are Alego-Usonga, Gem, Ugenya, Ugunja, Bondo, and Rarieda. Major agro-ecological zones are lower midland and upper midland zones. Siaya County is dominated by Ferralsols soils and based on key characteristics of its climate is classified as sub-humid. Target population was the farming households in five randomly selected wards of Gem Sub County.

Cochran formula Hasan and Kumar (2024), was used to determine the sample size of the farmers who were interviewed. The formula is specified as:

$$N = \frac{Z^2 pq}{d^2} \text{ ……………………………………1}$$

Where N = desired population sample size, Z = (1.96) represents the standard normal deviate at 95% confidence level, p = (0.5) = estimated proportion of farmers having characteristics under observation in the population targeted, $q = 1 - p = 0.5$ and is the proportion of the population without the characteristics being measured. d is the significance level. In total, 384 farming households formed the sample size.

Multistage stratified sampling procedure was used to randomly select a sample comprising 384 farming households from the study area. Five wards were randomly selected from Gem Sub County, Siaya County. These wards represented several community contexts, each of which may have had distinct farming methods, farming resources, and socioeconomic traits. Through ward-based stratification, the study made sure that every Gem Sub County sub-region was included in the sample, enabling a more thorough picture of the agricultural households throughout the county. From each randomly selected ward, one location was randomly selected and all the farming households from the five randomly selected locations formed the sampling frame. The probability proportionate to size procedure was used to get the total number of farming households to be interviewed from the sampling frame. This total number of households to be interviewed in each location was calculated by dividing the total number of farming households in each selected location by the total number of farming households in the five locations, then multiplying by the sample size as indicated below;

$$M = \frac{n}{N} x384 \text{ ………………………………2}$$

where, M = the total number of farming households to be interviewed in each location, n = total number of farming households in each location, and N= total number of farming households from the five locations.

***Data collection*:** To ensure consistency in addressing important variables and to allow for flexibility in responses, a semi-structured questionnaire was used to collect data for this study. For a thorough grasp of farmers' experiences with the use of biochar, enumerators were able to ask follow-up questions. The head of the household was the main respondent to the questionnaire, which was distributed at the household level. The oldest sibling was interviewed in lieu of the household head when the head was not accessible, guaranteeing that the responses were from someone who was familiar with the farming methods used by the household. Data on adoption and intensity of adoption of biochar was collected from the farming households. To measure the dependent variable, biochar adoption, farmers were asked if they had included biochar into their farming practices. The farmers' answers indicated whether or not adoption had taken place. With replies expressed as a percentage of the total land area, adoption intensity was also evaluated by calculating the percentage of the farm's land that was applied with biochar. This allowed for the measurement of both the frequency of adoption and the extent of its use.

***Study models*:** To analyze data on socio-economic factors influencing adoption intensity of biochar among farming households in the sub-humid regions of Western Kenya, Heckman selection model was used. The model suited this study because it corrects selection bias. To correct selection bias, an Inverse Mills Ratio (IMR) was computed from the selection equation (Probit Regression Model) and was included in the second outcome equation (Ordinary Least Squares/OLS) as one of the explanatory variables Verma *et al*. (2024), to estimate adoption intensity of biochar. The dependent variable was a binary outcome;1-if biochar is adopted, 2-otherwise. The selection equation is modelled as follows;

$$Z^* = \beta_1 X_1 + \varepsilon \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

$Z = 1$ if $Z^* > 0$, Z= otherwise, where, Z^*= latent variable representing the probability to adopt biochar, X_1 = the vector of independent variables, the socioeconomic factors, β_1 is the vector of coefficients for socioeconomic factors while ε is the error term. The latent variable (Z_i^*) is not observed, but we do observe the binary variable (Z_i) whether a farmer adopted biochar or not. Then, the binary variable was given by;

$$Z = \begin{cases} 1, and if\ Z^* > 0 \\ 0, otherwise \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

To correct the selection bias, an IMR was calculated from the probit model predicted probabilities, where,

$$\text{IMR or } \lambda = \frac{\phi X_1 \beta_1}{\varphi X_1 \beta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Where, ϕ = the standard normal probability density function and φ= the cumulative distribution function for a standard random variable. The value of λ was unknown, but parameters β_1 were estimated using probit model based on the observed binary outcome. The IMR or $\lambda = \frac{\phi X_1 \beta_1}{\varphi X_1 \beta_1}$ was then inserted into regression equation to account for non-random selection bias.

Ordinary least square model was run as the outcome equation, which was therefore modelled as follows;

$$\gamma = \beta_2 X_2 + \lambda p + \varepsilon \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

γ = the dependent variable (intensity of adoption) which was determined by the proportion of land treated with biochar, X_2= socioeconomic factors and β_2 =the coefficients of the socioeconomic factors, λ = the IMR gotten from the probit model p = the coefficient of the IMR and indicated the direction and presence of selection bias while ε = the error term.

As mentioned earlier, this study utilized the Heckman Selection Model introduced by Heckman (1979), as it effectively addresses sample selection bias by recognizing that the choice to participate (or be included in the sample) might be affected by variables that also influence the outcome of interest (Abbasi *et al.*, 2021). Initially, the Heckman Selection Model was assessed for data analysis. The generated IMR was significantly positive, suggesting the presence of selectivity bias and leading to rejection of the null hypothesis, which claims that there is no unobserved selection process affecting the adoption intensity equation. The positive sign of the IMR indicates that the error terms within the selection (probit)and outcome (OLS) models are correlated. For this, a two-stage model was adopted, benefiting from its ability to correct selectivity bias.

Moreover, the Heckman Selection Model is favored for its remarkable efficiency in utilizing either the same or different explanatory variables across both stages (adoption of biochar in the first stage and intensity of adoption in the second) of the analysis (Muñoz *et al.*, 2023). Before conducting the analysis, the suitability of the model was evaluated using the maximum likelihood method. The Wald chi-square for the model proved significant (Wald chi2 (9) = 262.23 Prob > chi2 = 0.0000), indicating that the model is robust since the coefficients are jointly significant. This suggests that all explanatory variables included in the model collectively impacted households' likelihood of engaging in the adoption of biochar.

RESULTS

Diagnostic tests were first run to ensure the **validity** and **reliability** of the statistical model and results. Data was then processed in two steps. First, a summary of the socioeconomic profiles of the survey respondents is provided in the first part while the econometric results on the socio-economic factors influencing adoption and adoption intensity of biochar among

Table 1. Hypothesized explanatory variables on adoption of biochar and their expected effect.

Variable	Nature of variables	Variable definition and measurement	Expected effect
Marital status	Categorical- Multinomial	1=married, 2=single, 3=widowed, 4=divorced	+/-
Gender	Categorical- Binary	1 if female, 2 male	+/-
Education level	Categorical- Multinomial	1=never went to school, 2=primary, 3=secondary, 4=college, 5=university	+
Age	Continuous	Age of the household head in years	+/-
Land in acres	Continuous	Farm land size in acres	+/-
Land used in farming	Continuous	Farm land devoted to farming in acres	+
Awareness of biochar	Categorical- Binary	1 of a household is aware of biochar, 0 otherwise	+
Terms of land ownership	Categorical- Multinomial	1=owned with a title deed, 2=owned without a title deed, 3=leased, 4=inherited	+/-
Access to credits	Categorical- Binary	1 if the household head has access to credits, 0 otherwise	+

farming households is presented using Heckman's two-stage model.

***Diagnostic tests*: ** Normally distributed errors are crucial for valid statistical inference. Therefore, normality test was carried out to check if the errors were normally distributed. To achieve this, the study applied the Jarque-Bera test to examine the normality assumption of the errors. Results revealed that the tests' null hypotheses could not be rejected because the p-value (0.216) was greater than the threshold of significance level of 5%.

Heteroscedasticity was also tested to examine if the variance of the errors was constant across different levels of the predictors. This test was important because heteroscedasticity violates the assumption of homoscedasticity, which assumes that the variance of the errors is constant (Virgantari *et al.*, 2024). This test was crucial because inconsistence variance of the errors can lead to unreliable coefficient estimates. This study applied robust standard errors to the regression model which adjusted the standard errors thus making them more reliable.

Multicollinearity was tested to determine if two or more regressors were correlated in the regression model. This was crucial because correlation of two independent variables within a regression model do not provide unique information as they overlap in what they explain in terms of variation in the dependent variable. To solve this, the study applied the Variance Inflation Factor (VIF) test as presented in Table 2.

As per Table 2, results for VIF indicate that there is no multicollinearity problem among the study variables since the mean VIF is less than 10.

***Descriptive statistics*: ** Table 3. and Table 4. show descriptive statistics of the variables utilized in the model. These statistics provided a comprehensive overview of the variables associated with biochar adoption among farming households in Siaya County. Results in Table 3 show that the study interviewed 461 farming household heads from which 85 (18.4%) had adopted biochar in their farming practices while the remaining 376 (81.6%) of respondents had not integrated this practice into their farming practices.

Table 2. Variance inflation factor.

	VIF	1/VIF
Land used in farming	4.592	0.218
Land in acres	4.437	0.225
Marital status	1.378	0.726
Gender	1.377	0.726
Education level	1.351	0.740
Access to credits	1.267	0.789
Awareness of biochar	1.253	0.798
Age	1.228	0.814
Off-farm income	1.146	0.873
Terms of land ownership	1.078	0.927
Mean VIF	1.911	

The results in Table 3. examine the relationship between various socio-economic factors and the adoption of biochar. The Chi-square (χ^2) values indicate which factors have a significant impact on biochar adoption. Data shows that 19.62% of female participants and 17.82% of male participants had adopted biochar into their farming practices. Among non-adopters, 80.38% were female and 82.18% were male.

Education level was found to have a significant effect on biochar adoption. The Chi-square value of 54.463 indicated that it was well above the threshold for statistical significance ($p < 0.05$). Secondary level of education had the highest (45.34%) number of interviewees. Among adopters, 45.45% of the farmers had gone up to university, while 4.83%, 20.57%, and 20.83% had acquired primary, secondary, and college levels of education respectively which were crucial for understanding the benefits of soil amendments in their farming practices. Furthermore, the results suggest that farmers with higher levels of education are more likely to adopt biochar. This may be due to greater awareness of the

Table 3. Summary statistics of categorical variables affecting biochar adoption.

		Frequencies (percentages)			
		Adopters	**Non-adopters**		**χ²**
Variable	**Categories**	**(n=85)**	**(n=376)**	**Total=461**	
Gender	Female	31 (19.62)	127 (80.38)	158 (34.27)	0.22
	Male	54 (17.82)	249 (82.18)	303 (65.73)	
Education level	None	0 (0.00)	17 (100.0)	17 (3.69)	54.46**
	Primary	7 (4.83)	138 (95.17)	145 (31.45)	
	Secondary	43 (20.57)	166 (79.43)	209 (45.34)	
	College	5 (20.83)	19 (79.17)	24 (5.21)	
	University	30 (45.45)	36 (54.55)	66 (14.32)	
Marital status	Married	69 (18.9)	296 (81.1)	365 (79.16)	2.02
	Single	5 (19)	21 (80.77)	26 (5.64)	
	Widowed	10 (14.71)	58 (85.29)	68 (14.75)	
	Divorced	1 (50)	1 (50)	2 (0.43)	
Access to credits	Access	74 (36.45)	129 (63.55)	203 (44.03)	78.28**
	No access	11 (4.26)	247 (95.74)	258 (55.97)	
Terms of land ownership	Owned with a title deed	40 (21.74)	144 (78.26)	184 (39.91)	5.52
	Owned without a title deed	8 (15.09)	45 (84.91)	53 (11.50)	
	Leased	29 (18.59)	127 (81.41)	156 (33.84)	
	Communal	8 (15.09)	45 (84.91)	53 (11.50)	
	Inherited	0 (0.00)	15 (100)	15 (3.25)	
Awareness of biochar	Aware	81 (50.31)	80 (49.69)	161 (34.92)	167.12**
	Not aware	4 (1.33)	296 (98.76)	300 (65.05)	

*** p<.05*

Table 4. Summary statistics of continuous variables affecting biochar adoption.

Variable	**Mean**	**Std. Dev**	**Min**	**Max**	**T**
Age	47.57	13.02	24	90	0.294
Total land owned in acres	2.354	1.646	0.375	12	-8.560**
Land used in farming	1.508	1.191	0.200	0.9	-11.811**

*** p<.05*

benefits and methods of using biochar, as well as a higher capacity to access or understand the technology.

Results for the marital status revealed that among the adopters, 18.9% are married, 19% are single, and 14.71% are widowed. In contrast, the marital status distribution among non-adopters is similar, with the majority being married (81.1%). These findings suggest that marital status does not appear to be a determining factor in whether individuals adopt biochar.

Access to credit was found to have a significant impact on adoption of biochar. With a Chi-square value of 78.278, which is highly significant ($p < 0.05$), results revealed that access to credit was a crucial factor that promoted adoption of biochar. A large proportion of adopters (36.45%) had access to credit, compared to just 4.26% of non-adopters. In contrast, a majority of non-adopters (95.74%) did not have access to credit. This indicated that access to financial resources, such as loans or credit, is an important aspect that encouraged more farmers to adopt biochar adoption. This could be because adopting biochar may involve costs for equipment or training, which those with credit access are better positioned to manage.

Awareness of biochar was by far the most significant factor affecting its adoption, with a Chi-square value of 167.121 ($p < 0.05$). The data revealed that 50.31% of adopters were aware of biochar, compared to just 1.33% of non-adopters. On the other hand, a large majority of non-adopters (98.76%) were not aware of biochar. This strongly suggested that being aware of biochar played a significant role in its adoption. Those who are informed about the benefits and uses of biochar are far more likely to adopt it, highlighting the importance of education and awareness campaigns in promoting its use.

Table 5. Probit regression; Socio-economic factors influencing adoption of biochar.

Variables	Parametric estimation				Marginal effect			
	Coefficient	St.Err.	z	P>|z|	Coefficient/ dy/dx	St.Err.	z	P>|z
Marital status	0.059	0.170	0.35	0.727	0.004	0.013	0.350	0.726
Gender	-0.042	0.267	-0.16	0.874	-0.003	0.020	-0.160	0.875
Education level	0.328	0.111	2.95	0.003	0.024**	0.010	2.440	0.015
Age	0.005	0.010	0.47	0.637	0.000	0.001	0.480	0.634
Total land owned in acres	-0.493	0.166	-2.97	0.003	-0.037**	0.015	-2.440	0.015
Land used in farming	1.006	0.227	4.44	0.000	0.075***	0.026	2.840	0.005
Terms of land ownership	-0.027	0.093	-0.30	0.767	-0.002	0.007	-0.290	0.769
Access to credits	0.847	0.246	3.44	0.001	0.063***	0.023	2.720	0.007
Awareness of biochar	2.134	0.273	7.81	0.000	0.159***	0.042	3.820	0.000
Constant	-4.451	0.957	-4.65	0.000				
Pseudo R2	0.5950		Number of obs.		461			
LR Chi2 (9) Log likelihood =	262.23-89.23		Prob > chi^2		0.000			

**** p<.01, ** p<.05, * p<.1*

Results from Table 4. indicate that farmers in this survey had an average age of 47.6 years however, the ages ranged from 24 to 90 in this group, which constitutes a generally older population of farmers. The t-test for age revealed that there was no statistically significant difference in the mean age between adopters and non-adopters of biochar. The test statistic was 0.2937, and the p-value was 0.7692, which is well above the conventional threshold of 0.05. This suggests that age is not a significant factor in determining whether an individual adopts biochar or not.

In terms of total land owned in acres, the sample population owned an estimated 2.4 acres of land but much diversity was evident as shown by a standard deviation of 1.6. The t-test for total land owned in acres showed a significant difference between adopters and non-adopters. The test statistic was -8.5601, and the p-value was 0.0000, which was highly significant. This indicated that adopters of biochar owned significantly more land than non-adopters. Therefore, land ownership was found to be an important factor influencing biochar adoption. It suggests that individuals with more land may be more likely to adopt biochar, possibly because they have more agricultural operations that could benefit from its use.

With regard to the total land used in farming, a mean score of 1.51 showed that agricultural activities were carried out on certain pieces of land by a portion of households, with differences in sizes among the households. The t-test for land used in farming revealed another significant difference. The test statistic was -11.8110, with a p-value of 0.0000, indicating a highly significant difference. Adopters of biochar used more land for farming compared to non-adopters. This suggested that adopters were more likely to engage in farming on a larger scale than non-adopters. It could imply that individuals who are more involved in farming, and who manage larger plots of land for agricultural purposes, are more inclined to adopt biochar, likely due to the potential benefits it offers for soil health and productivity.

DISCUSSION

***Socio-economic factors influencing adoption of biochar among farming households in the sub-humid regions of Western Kenya*:** A probit regression model was run in the first stage of the Heckman selection model to determine the socio-economic factors affecting adoption of biochar.

Table 5. shows the results of the first stage of Heckman selection (Probit regression) and the marginal effect of probit results of the socio-economic factors influencing the likelihood of the farming households to adopt biochar in their farming techniques. Nine explanatory variables were run in the model. Of these, five variables had a significant impact on the adoption of biochar: education level, total land owned in acres, land used in farming, access to credits, and awareness of biochar. However, marital status, gender, age, and the terms of land ownership had insignificant effects.

Specifically, the marginal effect for education was positive and statistically significant at a 5% level. Holding all other factors constant, this implied that each additional unit of education increased the likelihood of adopting biochar by approximately 2.44%. This suggests that an increase in the level of education of the farmer increases the probability of adopting biochar, reinforcing the result from the probit regression. Education is a key factor in facilitating biochar adoption, possibly through greater awareness of its benefits and the ability to understand the long-term value of the technology. Formal education exposes people to getting information on sustainable farm inputs and emerging technologies in agriculture sector. In addition, exposure to education shape the ability of farmers to make informed decisions based on identified information of cost and benefit.

These findings were in line with that of Diriba and Kebede (2024), who found that large number of farmers who had adopted inorganic fertilizers were better in education compared to the non-adopters. The findings also support the results by Chao *et al*. (2024), who reported that farmers who were highly educated were more likely to adopt sustainable agricultural practices. Further, the finding support the research done by Zenbaba *et al*. (2024), who reported that increase in education level by the household head increased adoption of wheat production package by 1.52%.

As hypothesized, total land in acres owned by the household was found to be negatively and statistically influenced the likelihood of biochar adoption at a 5% level. This implied that with each additional acre of land, the probability of biochar adoption was reduced by approximately 3.68%. This finding suggests that larger landowners are less likely to adopt biochar, likely due to the increased cost or logistical challenges associated with applying biochar on larger plots of land. As mentioned earlier, larger landowners may also be more entrenched in conventional farming practices and less inclined to experiment with new technologies. The finding is supported by Zakaria *et al*. (2020), who reported a negative impact of the size of farmland on adoption of agricultural technologies. However, this finding is contrary to the findings of Chao *et al*. (2024), who reported that the likelihood of adopting sustainable agricultural practices increased with an increase in the size of farmland owned by the farmer. The finding also contradicted with that of Wongnaa *et al*. (2024), who found that farmers who owned large tracks of land were more inclined to adopting a new technology as they can allocate a portion of their land to experiment the technology. This discrepancy suggests that supporting farmers with large tracks of land to adopt agricultural technologies can lead to increased agricultural productivity and increased food security.

As expected, the size of land used in farming was positive and statistically significant at 1% level. This implied that, all other variables held constant, when an additional unit of land used for farming increases by one unit, the probability of adopting biochar increases by 7.51%. This suggests that farmers who actively cultivate more land are more likely to adopt biochar, perhaps because the benefits of biochar in terms of soil improvement and yield enhancement are more apparent to farmers with larger, more intensive operations. The greater the land area under cultivation, the more likely farmers are to experiment with and benefit from the adoption of biochar. The finding corroborates existing evidence by Arhin *et al*. (2024), who reported that farmers who had relatively small sizes of farmland were less likely to use sustainable agricultural practices because the cost of adopting these technologies could be high relative to the size of land they had.

Access to credits is also a major factor influencing the household's head attitude towards adopting biochar. The marginal effect of access to credits by the household head was positive and significant at a 1% level, indicating that access to financial resources increases the probability of adopting biochar. Specifically, each additional unit of access to credits increases the likelihood of adoption by about 6.32%. This result highlights the importance of financial accessibility: farmers who easily access credits or loans are more likely to invest in biochar, as it may involve upfront costs for purchasing and applying the material. This finding confirmed the previous research by Miine *et al*. (2023), who found that farmers who accessed credits were more inclined to adopting digital agricultural solutions because they became endowed with financial resources and therefore could afford multiple solutions compared to farmers who did not have access to credits. Further, the finding corresponds with the report given by Ngango *et al*. (2023), who found that farmers who accessed credits had a higher likelihood of adopting agroforestry technology as compared to farmers who had low access to credits.

The marginal effect for awareness of biochar is very large and statistically significant at a 1% level. All other factors held constant, an increase in awareness of biochar to the farmer increases the likelihood of adoption by 15.93%. This reinforces the earlier probit regression result, where awareness had a very strong effect on adoption. It suggests that increasing farmers' knowledge of biochar, through educational programs, media, or extension services, has a substantial effect on adoption behavior. Awareness likely facilitates understanding of biochar's benefits, making farmers more likely to consider it as a viable agricultural practice. In addition, farmers who are better informed about the benefits of biochar; such as improving soil fertility, increasing carbon sequestration, and enhancing crop yields, are more likely to incorporate it into their farming practices. A similar viewpoint was reported by Asante *et al*. (2024), who reported that farmers who had received information about climate smart agricultural practices were more inclined to adopting these practices compared to farmers who had never heard about these practices. As reported by Kiprotich *et al*. (2023), awareness of a technology is a key factor that affects decision to adopt the technology. The results however contradicted with that of Arhin *et al*. (2024), who reported that awareness of sustainable agricultural technologies did not affect farmers' decision to adopt sustainable agricultural technologies.

Socio-economic factors influencing adoption intensity of biochar among farming households in the sub-humid regions of Western Kenya**:** The second stage of the Heckman selection model was run to identify the degree of influence of socioeconomic factors on intensity of adoption of biochar using the Ordinary Least Squares (OLS) regression model. The coefficient of the lambda or IMR was found to be positive at 5% significance level. The IMR significance reveals that selection bias occurred and hence the effectiveness of using the Heckman Selection Model to cater for this selection bias. Further, the positive sign of the IMR reveals that the error terms of the selection equation and the outcome equation were correlated.

Table 6. shows the OLS regression results of variables that had an impact on adoption intensity of biochar among smallholder farmers. Out of the ten independent variables, five were found to have a significant effect on adoption intensity of biochar. Education level, access to credits, awareness of biochar and lambda were found to have a positive impact on adoption intensity of biochar while terms of land ownership affected adoption intensity of biochar in a negative way. Marital status of the household head, gender, age, total land in acres and land used in farming were found to be insignificant in influencing intensity of biochar adoption.

Table 6. OLS regression; socio-economic factors influencing adoption intensity of biochar.

Variables	Coef.	Robust St.Err.	z	P>|z|
Marital status	-0.018	0.086	-0.21	0.832
Gender	-0.213	0.130	-1.64	0.101
Education level	0.484**	0.194	2.50	0.014
Age	0.005	0.004	1.10	0.270
Total land owned in acres	-0.102	0.140	-0.73	0.466
Land used in farming	0.052	0.240	0.22	0.828
Terms of land ownership	-0.277**	0.132	-2.09	0.044
Access to credits	0.729*	0.254	2.87	0.004
Awareness of biochar	1.176**	0.461	2.55	0.013
Constant	1.943	2.048	0.95	0.343
Number of obs.	461			
Selected	85			
Non-selected	376			
Wald chi2(9)	34.38			
Prob > chi2	0.0001			
Mills lambda	0.2919**(0.101),P>|z|=0.004			
Rho	0.9363			
sigma	0.4246			

*** $p<.01$, ** $p<.05$, * $p<.1$

From the first and second stages of the model, level of education of the head of the household, awareness of biochar and access to credits significantly affect both the decision to adopt biochar and the intensity of adopting biochar, with expected sign. Level of education of the household head and awareness of biochar positively and significantly influences adoption intensity of biochar at 5% level while access to credits positively influences adoption intensity of biochar at 1% significance level. As predicted, terms of land ownership negatively affect adoption intensity of biochar at 5% level.

As expected, education level of the household head had a positive and a significant influence on the adoption intensity of biochar at 5% level. Holding all other factors constant, each additional increase in education level would result to a relative increase of farmer's proportion of land under biochar by 0.48. This means that, farmers who have higher levels of education are more likely to understand the long term benefits of biochar, both as a soil amendment and also as a sustainable way of reducing costs of buying other soil inputs (Osabohien, 2022). This understanding makes them to be more willing to adopt biochar at a larger scale, and significantly devote biochar into their farming practices. Further, farmers with a greater educational background are likely to experiment this new technology at a larger scale, motivated by its benefits, increasing its adoption intensity. The finding is consistent with that of Getnet and Debebe (2024), which reported that farmers who were more educated adopted more agricultural inputs than uneducated ones. Further, the finding is supported by Kaba and Emana (2024), who found that a high education level increased the adoption intensity of soya bean production.

As predicted, awareness of biochar was found to positively and significantly affecting adoption intensity of biochar at 5% level. Any additional increase in awareness of biochar by one unit will lead to an increase in the proportion of land under biochar by 1.18, holding all other factors constant. This means that, if farmers are more aware of the benefits of biochar and its application methods, they are more likely to apply it on large portions of their farmlands. More awareness increases the confidence to apply and experiment it more widely, increasing its adoption intensity. This finding confirmed the previous research by Cui *et al*. (2022), which reported that awareness of smallholder farmers about green production technologies increased their willingness and intensity to adopt this technology. Further, the finding also corresponds with that of Chuang *et al*. (2020), who reported that increased knowledge about smart agriculture technology led to more adoption of the technology.

As hypothesized, access to credits positively impacted adoption intensity of biochar at 1% significance level. This implied that, when all other factors are held constant, each unit increase in access to credits will be associated with increased adoption intensity of biochar by 0.73. This is so because financial support through increasing credit access to farmers reduces the cost barriers that might limit farmers from applying biochar in large scale. When credits are readily available and easily accessible, farmers will be more encouraged to apply biochar in large portions of their land, increasing adoption intensity of biochar (Yadav and Rao, 2022). This finding shows consistency to that of Chao *et al*. (2024), who confirmed that farmers who accessed credits had a higher adoption intensity of sustainable agricultural practices. Further, these results align with that of Addison *et al*. (2023), who revealed that credit access increased adoption intensity of improved rice technology. Generally, limited credit access is a barrier to adoption of agricultural innovations by most resource poor farmers. Government should therefore optimize on providing credits to farmers to boost technological innovations (Mapanje *et al.*, 2023).

Terms of land ownership negatively and significantly affected adoption intensity of biochar at 5% level, as predicted. This means that, holding all other factors constant, if the security of land ownership reduces by an additional unit, adoption intensity of biochar will reduce by 0.28. Farmers who have insecure land tenure and short term land lease may not be motivated to venture into farm technologies that require a long term commitment such as biochar application. The benefits of biochar might not be attractive to them because of their uncertainty to retain land for long. These farmers will therefore apply biochar in small portions of land or might not apply it at all, reducing its adoption intensity. Farmers with secure land tenure are highly encouraged to adopt agricultural technologies (Ngaiwi *et al.*, 2023). This finding is in line with that of Addison *et al*. (2023), who reported that land ownership increased the intensity of adopting improved rice varieties. Additionally, the results are in line with those of Ngango *et al*. (2023), who reported that land ownership had a positive and significant influence on adoption of agroforestry practices.

The IMR had a positive and significant effect at 1% level. This suggests that, after accounting for the sample selection bias, farmers who had adopted biochar into their farming practices were also more likely to adopt it in a large scale into their farming practices. This implies that certain factors such as education level of the household head, access to credits, and awareness of biochar do not only influence the decision to adopt biochar but also influences the intensity of biochar adoption. Further, the positive coefficient of the IMR suggests that adoption of biochar is not random, and farmers who choose to adopt biochar tend to adopt it more intensively.

***Conclusion*:** The study reveals that awareness of biochar, access to credits, total land used in farming, and education level positively and significantly influences adoption of biochar while total land owned in acres negatively and significantly influences adoption of biochar. Similarly, awareness of biochar, access to credits, and education level positively and significantly influences adoption intensity of biochar while terms of land ownership negatively and significantly influence adoption intensity of biochar. In light of these findings the Ministry of Agriculture, through the Department of Agricultural Extension should take the initiative to promote the advantages of biochar, especially with regard to increasing crop yields and soil fertility, while development organizations should offer financial assistance, such as credit schemes or subsidies, and training programs to help farmers overcome socio-economic obstacles and increase biochar adoption. Additionally, policymakers should urge farmers to work together through groups and cooperatives to lower the cost of biochar production. These actions can promote the use of biochar and its environmental and economic benefits for smallholder farmers.

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