UNIVERSITY FOR DEVELOPMENT STUDIES

ENHANCING FARM PERFORMANCE AND WELFARE OF GROUNDNUT-PRODUCING HOUSEHOLDS: THE ROLE OF BIOCHAR ADOPTION IN UPPER WEST REGION OF GHANA

BY

HUBEIDA ABDULAI

(UDS/DEC/0009/21)

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DEPARTMENT OF AGRICULTURAL AND FOOD ECONOMICS

FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCES

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THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL AND FOOD ECONOMICS, FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCE, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY DEGREE IN AGRICULTURAL ECONOMICS

MARCH, 2026

DECLARATION

I, Hubeida Abdulai, declare that this thesis titled **"Enhancing Farm Performance and Welfare of Groundnut-Producing Households: The Role of Biochar Adoption in Upper West Region of Ghana"** is the outcome of my independent work and does not contain any idea or material previously published or submitted to any university, for the purpose of obtaining a similar degree.

Hubeida Abdulai 30/03/2026
(Student) Signature Date

Supervisors

We, the supervisors, declare that this dissertation is entirely the student's own, which was supervised following the rules and guidelines set by the University.

Prof. Awal Abdul-Rahman 30/03/2026
(Principal supervisor) Signature Date

Prof. Benjamin Tetteh Anang 31/03/2026
(Co-supervisor) Signature Date

Prof. Benjamin Tetteh Anang 31/03/2026
(Head of Department) Signature Date

ABSTRACT

Agricultural sector has a formidable twofold challenge of producing twice the world food by 2050 to sustain the world population and at the same time fight the impacts of climate change and reduce emission of its greenhouse gases by adopting sustainable agricultural methods. This study examines the determinants and impacts of biochar adoption on farm performance, commercialization, and welfare of smallholder groundnut farmers in the Upper West Region of Ghana. The used a survey data from 564 groundnut farmers through a multistage sampling method. The recursive bivariate probit, endogenous switching regression (ESR), and stochastic production frontier (SPF) models were employed to analyze the impact of biochar adoption on farm performance, commercialization, and welfare. The results show that access to credit, agricultural extension services, training programs, farm size, and farmer-based organizations significantly enhance biochar adoption. Adoption of biochar increased commercialization by 2.5-5%, implying a positive relationship. Also, biochar adoption was found to enhance farm household welfare with adopters gaining extra GH₵0.94 in per capita income per month and GH₵0.97 in per capita expenditure per month. The study also found biochar adoption to improve groundnut output and technical efficiency with adopters achieving 42-46% higher predicted yields. Based on the findings, the study recommends that policymakers should institute community-based biochar production systems that will ensure quality control, reduce production costs, and expand access to biochar. Local governments, research institutions, and development agencies should strengthen farmers policies and programs to expand sensitization and logistics that can help farmers enhance their adoption of biochar. For instance, improved access to agricultural extension services from government, NGOs or private institutions could provide farmers with insights to adopt biochar, since extension access significantly and positively affect biochar adoption. Provision of tailored credit schemes to meet the financial needs of smallholder farmers facilities through group loans and other credit alternatives with flexible payment modes for farmers could enhance farmers' adoption of biochar..

DEDICATION

This thesis work is dedicated to my lovely husband, Prof. Amin Alhassan, for believing in me, sponsoring this degree and always wants the best for me and our adorable children.

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LIST OF ABBREVIATIONS AND ACRONYMS

AfCFTA	African Continental Free Trade Area
ATE	average treatment effect
ATET	Average treatment effect on the treated
ATT	Average Treatment Effects on the Treated
CSA	Climate-Smart Agriculture
CSATs	climate-smart agricultural technologies
ESR	Endogenous Switching Regression
ESRM	Endogenous Switching Regression Model
FBO	farmer-based organisation
FCS	food consumption score
FIMLE	Full Information Maximum Likelihood Estimation
HDDS	household dietary diversity score
IMR	inverse Mill's ratio
LPM	Linear Probability model
LR	Likelihood Ratio
MESR	multinomial endogenous switching regression
MLE	maximum likelihood estimation
MMT	million metric tons
MNL	multinomial logit model
MTE	Metafrontier Technical Efficiency
MVP	Multivariate Probit Model
NPV	net present value
OLS	Ordinary Least Squares
PSM	Propensity Score Matching
RBPM	Recursive Bivariate Probit Model

SAPs	sustainable agricultural practices
SDG	Sustainable Development Goals
SLF	Sustainable Livelihood Framework
SPF	Stochastic Production Frontier
SPSS	Statistical Package for the Social Sciences
TAM	Technology Acceptance Model
TE	Technical Efficiency
TGR	Technology Gap Ratio
USAID	United States Agency for International Development
UTAUT	Unified Theory of Acceptance and Use of Technology

CHAPTER ONE

INTRODUCTION

This chapter outlining the background of the study, followed by the problem statement, research objectives, and research questions. It further presents the research hypotheses, justification of the study, and concludes with the organization of the remaining chapters. This opening chapter aims to give readers a straightforward grasp of the study's reasoning, main focus, and potential impact, all set against the bigger picture of agricultural technology adoption, sustainability, and climate-smart growth in Ghana.

1.1 Background of the Study

Among the challenges that define agricultural issues in the twenty-first century globally is the question of sustainable doubling of food production by 2050 while keeping climate change and greenhouse gas emissions at a minimum (Wijerathna-Yapa & Pathirana, 2022). In addition, severe soil fertility depletion has resulted in declining agricultural productivity due to reduction of soil organic matter (Getachew, 2017). In response to this challenge, Climate-Smart Agriculture (CSA) paradigm has been developed and it places greater emphasis on practices that are adaptable, create resiliency, and achieve mitigation. Under this context, biochar has been of increasing interest as a multifunctional soil amendment with the possibility to solve several production and environmental limitations.

Biochar is a porous material that is rich in carbon and is formed by subjecting biomass, consisting of crop residues, wood, or other organic waste, to low or no oxygen thermal decomposition called pyrolysis (Sri Shalini et al., 2020). Biochar is described as a black carbon that is produced intentionally to manage carbon for climate change mitigation purposes combined with a downstream application to soils for agricultural effects. Biochar has high stability, which means that it can remain in the soil for decades (Joseph et al., 2021). Its agronomic and economic potential is supported by the empirical evidence. For instance, studies including (e.g., Islam et al., 2021; Cen et al., 2021; Blanco-Canqui, 2021; Al-Omran et al., 2021; Gebisa and Regasa, 2024) have shown that the application of biochar can positively influence the bulk density of soils, soil porosity, water storage and utilization, aggregate stability and soil organic carbon. It also amends the carbon depleted and acidic soils, help adapt to adverse impact of climate change (Getachew *et al*., 2017; Peter , et al., 2022). According to Danso et al. (2023), the cost of using biochar in rice production was found to be high at the initial stage, but in the residual stages the effects of biochar prove beneficial as the ratio of benefits to costs increases from 0.54 to 1.33 at the first season and from 1.22 to 1.84 on the residual fields. indicating the economic feasibility of biochar in the long term.

Groundnut (Arachis hypogaea L.) is one of the most significant oilseed crops in the world (Lafarga, 2021; Motagi et al., 2022) and one of the main pillars of the agricultural economy in Ghana, especially in the northern Ghana (Kankam et al., 2021; Lafarga, 2021). Groundnut has a multi-dimensional value; in addition to the fact that it is a source of edible oil, high-quality protein, and essential vitamins, the groundnut fulfills an ecological service of biological fixation of nitrogen, naturally enriching the land with future crops (Rajput et al., 2024; Mitra et al., 2025). This versatility makes it a non-negotiable lifeline for millions of smallholders, particularly those operating in the fragile economies of tropical and subtropical regions (Kpienbaareh et al., 2022). The modern geography of groundnut cultivation spans over 100 countries, though the bulk of the world's output is concentrated in Asia 65%, Africa 26% (Okello et al., 2010; Chilwal et al., 2025).

Projections for the 2025/26 season suggest a fascinating shift in how the world produces this legume. According to the USDA-FAS (2025), the total land area dedicated to groundnuts is actually contracting slightly, falling to about 29.56 million hectares. However, total production is paradoxically expected to rise to approximately 51.74 million metric tons. This indicates a global move toward sustainable intensification, where improved technologies and smarter management are allowing farmers to harvest more from less land.

On the contrary, Ghana’s National groundnut output is expected to slip by about 6.2 percent, a contraction driven not by a loss of land, but by the erratic rainfall and dry spells that have plagued recent cropping cycles (USDA, 2025). This pattern confirms a sobering reality: Ghana’s groundnut production is structurally fragile, and productivity is still largely at the mercy of the weather. Beyond the yield gap, there is a hidden danger: aflatoxin. These toxic compounds are produced by *Aspergillus* fungi which can lead to devastating health problems, including liver cirrhosis and immune suppression (Dabuo et al., 2022). While drying crops properly after harvest helps, it cannot fix the contamination that starts in the soil. This makes soil-based preventive strategies like biochar essential for ensuring food safety.

Furthermore, “Decades of continuous farming and deforestation, without adequate nutrient return, have depleted the land (Vanlauwe et al., 2023). In northern Ghana where rainfall is unpredictable and the soil is naturally fragile; these factors create a cycle of poverty and food insecurity. The northern Ghana is actually uniquely positioned to lead a biochar revolution. The area produces massive amounts of agricultural "waste" specifically rice husks, maize stocks, soybean wastes and groundnut shells that could be converted into biochar. This would solve two problems at once: cleaning up environmental waste and providing an affordable way to restore soil fertility.

This study aims to bridge the gap between soil science and socioeconomic reality. By examining how biochar adoption affects the productivity, efficiency, and welfare of groundnut farmers, we hope to provide the evidence needed to back Ghana’s 2015 Climate-Smart Agriculture Policy. Ultimately, this research is about more than just dirt; it is about contributing to the Global Goals of ending poverty (SDG 1), achieving zero hunger (SDG 2), and taking meaningful climate action (SDG 13).

1.2 Problem Statement

Keeping farmland productive in Sub-Saharan Africa is arguably one of the most daunting tasks of our time. Across the continent, a combination of constant land use, deforestation, and a lack of nutrient recycling has triggered a sharp decline in soil fertility. This has created a worrying gap between what the land *could* produce and what it actually yields (Vanlauwe et al., 2023). Besides being a cheap source of protein and dietary variety, the crop also brings on board huge income and livelihoods to the rural population. However, groundnut production in the Upper West Region continues to face persistent constraints that limit productivity, profitability, and sustainability (Kotu *et al.*, 2022).

Biochar has been identified as an emerging climate smart technology enhancing the soil structure, nutrient retention, water retention, and captures carbon in the atmosphere (Sri Shalini et al., 2020; Joseph et al., 2021; Rogers et al., 2022; Kumar and Bhattacharya, 2021). Biochar enhances retention of nutrients in soils, Acidic soils stabilization, and growth of microorganisms leading to an increase in a crop yield and improved soils (Khan et al., 2024; Acharya et al., 2024). Aguirre et al. (2021) also demonstrated that good-quality biochar increased corn yield by 63.84 percent, enhanced nutrient retention, and recovered investment after three to four years, especially when carbon credits were considered. Bi et al. (2022) also established that when biochar was combined with organic manure and synthetic fertilizer, it enhanced yield, nitrogen use efficiency, and crop quality, but the cost of inputs made it less profitable in the short-run.

Despite these encouraging findings, the adoption of biochar and usage in Ghana is limited and unexplored. This low uptake is largely attributed to lack of coordinated national biochar programmes, poor institutional support and poor market connection of biochar products (Kumar et al., 2025; John et al., 2025; Pahari, 2025). More so, current literature overly focuses on the chemistry, how biochar affect soil fertility, soil density, porosity and organic carbon content (Islam et al., 2021; Cen et al., 2021; Blanco-Canqui, 2021; Al-Omran et al., 2021; Gebisa and

Regasa, 2024). John et al. (2025) investigated the production and economic viability of biochar for smallholder and family farms. Similarly, Pahari (2025) also assessed the economic viability of food produce using biochar. What is missing is the socioeconomic dimension of biochar. It remains unclear how biochar adoption affects farmers livelihood and their ability to participate in markets.

In the in northern Ghana, this is a missed opportunity. Farmers are sitting on a goldmine of agricultural "waste” rice husks and groundnut shells that could be turned into biochar. This would solve a pollution problem while simultaneously reviving their fields (Mitchell et al., 2022). The conversion of these residues to biochar would have the potential to not only improve the soil fertility but also address environmental pollution and improve crop production (Li et al., 2021; Mitchell et al., 2022; Acharya et al., 2024).

Ultimately, the core objective of this study is to bridge the gap between technical soil science and tangible human welfare. While the chemical and physical benefits of biochar are well-documented in controlled settings, its practical impact on the actual lives of those who use it remains the most critical, yet unanswered, question. This research seeks to move beyond the laboratory and into the fields in northern Ghana to determine if biochar is a truly transformative tool for smallholder farmers. To achieve this, the study evaluates the innovation through three primary lenses: farm efficiency, market participation, and overall household welfare.

The first point of inquiry centers on production efficiency. In an environment where resources are perpetually scarce, it is not enough to simply know that biochar can increase yields. We must understand if it allows farmers to optimize their existing inputs. By examining whether biochar enables groundnut farmers to produce more with the same or even fewer resources, we can determine if this is a viable pathway for sustainable intensification in the Upper West Region.

Beyond the farm gate, the study explores the vital link between soil health and agricultural commercialization. For the majority of smallholders in Ghana, farming has historically been a means of survival rather than a business venture. This research asks a fundamental question: can the productivity gains provided by biochar create the surplus necessary for farmers to move beyond subsistence? Transitioning from "farming for food" to "farming for profit" is a crucial step in breaking the long-standing cycle of rural poverty.

Finally, and perhaps most importantly, the study examines the direct effect of biochar adoption on household welfare. By tracking metrics such as income per capita and consumption expenditure, we can see how improvements in the dirt underfoot translate into a better quality of life. We are looking for the "real-world" ripple effects: a family's increased ability to afford better nutrition, invest in education, or access healthcare.

1.3 Research Questions

The main research question is does biochar adoption affect productivity, efficiency, commercialization, and welfare outcomes of groundnut farmers in the Upper West Region of Ghana. The study specifically asked;

1. To what extent does biochar adoption enhance agricultural commercialization among groundnut farmers in the Upper West Region of Ghana?
2. What are the measurable effects of biochar adoption on household welfare in the Upper West Region of Ghana?
3. In what specific ways does the adoption of biochar influence production efficiency within smallholder groundnut farming systems in the Upper West Region of Ghana?

1.4 Research Objectives

The main objective of this study is to assess the effects of biochar adoption on the productivity, efficiency, commercialization, and welfare outcomes of groundnut farmers in the Upper West Region of Ghana. Specifically, the study aims to:

1. Examine the extent to which biochar adoption enhances agricultural commercialization among groundnut farmers in the Upper West Region of Ghana.

2. Determine the effects of biochar adoption on household welfare among groundnut-farming households in the Upper West Region of Ghana.
3. Evaluate the impact of biochar adoption on production efficiency within smallholder groundnut farming systems in the Upper West Region of Ghana.

1.5. Significance of the Study

This research has an important academic, policy, and practical applicability, especially within the framework of current quest of Ghana to facilitate sustainable agricultural intensification and climate-resilient livelihoods. The production of groundnut in the Upper West Region is still an important aspect of rural livelihoods, and thus, it is a primary source of household income, nutrition, and food security. Nonetheless, the threats of the decreasing soil fertility levels, decreased input levels, unpredictable climate, and aflatoxin presence continue to be the elements that hinder productivity and profitability (Kankam et al., 2021; Vanlauwe et al., 2023). To overcome these limitations, novel and sustainable soil management approaches that would increase not only yield, quality of environment, but also rural wellbeing has to be developed, which, again, are in strong resonance with Climate-Smart Agriculture Policy (2015) developed by Ghana.

The research is especially important since it examines the socio-economic aspects of biochar adoption, which has been ignored in current literature. Although many investigations have been performed to elaborate biochar impact on the soil characteristics and the yield of crops (e.g., Blanco-Canqui, 2021; Bi et al., 2022; Joseph et al., 2021), much fewer studies have reported on the implication of biochar on efficiency of the farm, their presence in the market, and the household welfare opportunities within the systems of smallholder farms. This empirical gap will help the study to make a more holistic contribution to the existing body of knowledge on biochar as a climate-smart agricultural technology that has productivity and livelihood advantages.

Academically, the study contributes to the body of knowledge on sustainable soil management and agricultural transformation in Sub-Saharan Africa by ensuring that the empirical research has rigorous evidence on how biochar adoption affects the efficiency of farms, commercialization, and farm welfare outcomes at the farm level. The research also adds to the theoretical discussion of the agricultural innovation adoption by placing biochar in the context of the theory of farm household production and climate-smart agriculture.

Policymaking wise, the results will have practical implications to the policymakers, development partners, and agricultural extension agencies that aim to influence biochar and other sustainable practices of land management. Through illustrating the possible economic and environmental benefits of biochar, the research aims and objectives will be used in the formulation of specific interventions including subsidies, carbon credit schemes, local biochar production programs, and others that may promote uptake of biochar among smallholder farmers.

The study will result in practical knowledge at the community and practitioner level regarding how groundnut shells and rice husks, which are locally available and abundant bio-mass residues can be converted into biochar to enhance the fertility of the soil and the profitability of the farms. These lessons will be critical towards fostering the growth of their circular bio-economy that will reduce the volume of farm wastes, increase the stability of farms and environmental sustainability in the Upper West Region.

1.6. Organization of the study

This thesis is organized into five chapters. The first chapter is the introduction which presents the background of the study, the problem statement that informs the study, research questions and objectives, and the significance of the study. The second chapter, Literature Review, focuses on reviewing literature relating to key concepts (Groundnut production, biochar, commercialization, welfare outcomes, technical efficiency) used in the study, as well as empirical studies on biochar. The study area, research design, data types, sources, sampling procedures, conceptual framework, measurement of key variables, and methods of data analysis are presented in chapter three of this thesis. The fourth chapter presents and discusses the results (descriptive and objective-based) of the study. Finally, the fifth chapter presents a summary of the study, key findings, and relevant policy recommendations for MEDA, groundnut farmers, government, and other relevant stakeholders.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter focuses on reviewing relevant literature related to the study. It reviews on the concept of groundnut and biochar production, overview of groundnut production and trends, theories and conceptual framework of the study and the gap that informed the study.

2.2. Overview of Groundnut production

2.2.1. Groundnut (Arachis hypogaea): Agro-Ecological Requirements and Production Potential

The groundnut (Arachis hypogaea), also commonly referred to as the peanut, is one of the most adaptable oilseeds in the world, which is leguminous. Although it was traced back to South America, it has now become a staple of agriculture in the tropical and subtropical areas. Its colossal size is illustrated by recent statistics given by the Food and Agriculture Organisation (FAO, 2025): nowadays, the world harvests about 35.1 million tons of unshelled nuts every year, on more than 25.5 million hectares. It has a multi-dimensional value; in addition to the fact that it is a source of edible oil, high-quality protein, and essential vitamins, the groundnut fulfills an ecological service of biological fixation of nitrogen, naturally enriching the land with future crops (Rajput et al., 2024; Mitra et al., 2025).

In terms of geography, the geometrical range of groundnut production is 40 to 40^{o} N and 40 to 40^{o} S with the geometrical center being in warm weather (Gelaye and Luo, 2024). Not all varieties of the crop have the same lifecycle: sequentially branched ones are usually matured in 90 to 115 days, and alternately branched in 120 to 140 days.

Control of temperature is of paramount importance. The plant can thrive best with 22-28 C per day, anything below 18 C or more than 33 C starts to stress the plant and inhibit yields (Kalumba, 2021). Interestingly, although the groundnut is very sensitive and the germination rates at low temperatures have been shown to be much slower at temperatures below 20 C -the day length is not a concern to the groundnut. As one of the day-neutral plants, it grows and produces more because it is heat and moisture-driven rather than the amount of sunlight. In rainfed systems, the seasonal average rainfall of 500 to 700 mm that is spread uniformly is usually the standard of a normal harvest.

The physical and chemical properties of a particular soil are highly entrenched in determining the success of a groundnut crop. The groundnut unlike many other crops is well-known as picky with its environment, preferring the medium-textured soils that are well-drained, loose, and friable (Kumakech et al., 2022). This choice is not simply a question of promoting the growth of roots; this is a necessity within the special cycle of reproduction of the plant.

After the fertilization, the groundnut plant grows its own stalks known as pegs, which have to protrude through the earth surface to grow the pods in the security of the earth. In extremely heavy or compacted soil it becomes a formidable obstacle and these pegs are not able to penetrate the surface and eventually result in the loss of a lot of pods or a pop during the harvest.

The chemical balance of the soil is equally important in the health of crops besides the physical structure of the land. The groundnuts usually grow in a pH of between 6.0 and 6.5. Increased acidity below 6.0ppt causes the development of the aluminum or manganese toxicity causing the crop to be destroyed. Farmers should act by applying liming when the pH decreases below 6.0ppt. Although the groundnut has been hailed as having a symbiotically related relationship with root bacteria, that is why it can fix its own atmospheric nitrogen, it is not completely self-sustainable in the first place. A predictable low starting level of nitrogen, usually 10 to 20 kg/ha when plants are planted, is usually the determining factor of a healthy early growth and a robust root system (FAO, 2025).

Delicate nutrient balance is the last challenge in high yield soil management. The phosphorus demanded is also 15 to 40 kg/ha and the nutrient is still necessary to meet the energetic needs of the root growth as well as flowering (FAO, 2025). Potassium management involves a more delicate approach; on the one hand, it is important to approach the 25 to 40 kg/ha level because it is needed to maintain the overall health of plants, but, on the other hand, the excessive use will harm the yields inversely because it disrupts the absorption of other crucial elements. The most important perhaps of all is the use of calcium in the stage of pod-filling. Calcium (300 to 600 kg/ha) is the major defense against so-called empty pops to guarantee the shells are packed with high-quality and nutrient-rich kernels. The most complicated part of the groundnut is possibly water management. The water requirements of the crop change considerably as it progresses through its growth stages which is denoted by its crop coefficient (Kc). It begins at a low level (0.4-0.5) but increases in the mid-season (0.95-1.1) when the amount of moisture needed is the most (FAO, 2025).

2.2.2. Global Groundnut production

Often referred to as the “poor man’s nut,” the groundnut (*Arachis hypogaea L.*) has transcended its humble reputation to become one of the most significant industrial and food crops on the planet. Currently ranked as the thirteenth most essential food crop and the fourth leading source of edible oil, it occupies a central role in global nutritional security (Merem et al., 2021; Matanmi & Olabode, 2016). Beyond its obvious utility as a source of high-quality protein and vegetable oil, the plant provides a hidden environmental service by naturally enriching the soil through nitrogen fixation. This versatility makes it a non-negotiable lifeline for millions of smallholders, particularly those operating in the fragile economies of tropical and subtropical regions (Kpienbaareh et al., 2022).The modern geography of groundnut cultivation spans over 100 countries, though the bulk of the world’s output is concentrated in Asia 65%, Africa 26% (Okello et al., 2010; Chilwal et al., 2025). Projections for the 2025/26 season suggest a fascinating shift in how the world produces this legume. According to the USDA-FAS (2025), the total land area dedicated to groundnuts is actually contracting slightly, falling to about 29.56 million hectares. However, total production is paradoxically expected to rise to approximately 51.74 million metric tons. This indicates a global move toward sustainable intensification, where improved technologies and smarter management are allowing farmers to harvest more from less land.

Despite this overall growth, the progress remains frustratingly uneven. A massive "yield gap" often exceeding 200% separates the advanced, research-driven systems of the West and East Asia from the low-input farms of the Global South (USDA-FAS, 2025). This has resulted in a dual production system where global supply stability is maintained by a few high-performing regions, while others remain trapped by structural and environmental constraints. Asia remains the undisputed heavyweight in this arena, producing nearly two-thirds of the world's groundnuts (Ojiewo et al., 2020). China alone sets the global gold standard, achieving yields of 3.91 metric tons per hectare through aggressive government investment in research and mechanization (FAO, 2024). India follows as a secondary leader, bolstered by expanded irrigation and variety improvements that have stabilized its massive output (USDA-FAS, 2025).

In sharp contrast, the situation across Africa reveals a landscape of untapped potential struggling against systemic hurdles. While the continent boasts the largest cultivated area in the world roughly 13.5 million hectares it records the lowest average yields at just 1.32 metric tons per hectare (USDA-FAS, 2025). While Nigeria remains a significant producer, other nations like Sudan have seen their output plummet due to the dual threats of political instability and erratic rainfall. In countries like Ghana, Senegal, and Cameroon, production remains moderate but vulnerable. The underlying issue across the continent is a reliance on rainfed systems and unimproved seeds, making African farmers uniquely susceptible to climate shocks and income volatility.

Groundnut production systems in the Americas are generally characterized by higher levels of diversification and technological advancement. The United States continues to rank among the most productive producers globally, with average yields rising from 4.13 mt/ha to about 4.30 mt/ha in the 2025/26 season. Over the same period, the harvested area expanded from approximately 0.71 to 0.76 million hectares, resulting in an estimated output of 3.29 million metric tons—representing a 14.7 percent increase relative to the previous season (USDA-FAS, 2025). This expansion has been driven largely by the widespread adoption of precision farming tools, efficient irrigation technologies, and well-coordinated research–extension systems (Patil et al., 2021).

In contrast, groundnut production in Argentina is expected to contract sharply, declining by nearly 25 percent from 1.80 MMT to 1.36 MMT, mainly due to adverse climatic conditions and a reduction in cultivated area. Meanwhile, production levels in Brazil (1.15 MMT) and Mexico (0.08 MMT) are projected to remain broadly stable, although producers in both countries face increasing input costs and growing competition for arable land (USDA-FAS, 2025). In South and Southeast Asia, countries such as Pakistan (0.92 MMT), Myanmar (1.76 MMT), Indonesia (0.81 MMT), and Vietnam (0.38 MMT) are experiencing gradual but consistent growth. Vietnam's relatively high yield of 2.66 mt/ha reflects effective agronomic management and sustained public investment in improved seed systems and postharvest infrastructure (USDA-FAS, 2025).

At the global level, groundnut production has increased steadily over the past fifteen years, rising from roughly 38 MMT in 2010 to over 51 MMT by 2025. This upward trend has been driven primarily by yield improvements rather than by expansion of cultivated land (Chakuri, 2018; USDA-FAS, 2025). Despite this progress, marked productivity gaps persist across regions. Countries such as China and the United States regularly achieve yields exceeding 3.8 mt/ha, whereas average yields across much of Sub-Saharan Africa remain below 1.3 mt/ha. These disparities point to deeper structural differences in access to agricultural research, modern inputs, technology dissemination, and financial services. In many low-income settings, continued dependence on unimproved varieties, declining soil quality, and heightened climate variability continue to constrain productivity gains (Abady et al., 2019; Banla et al., 2018; Lokossou et al., 2022).

2.2.3. Groundnut Production in Africa

The crop is central to West and Southern Africa to the extent that it can be a major factor in the wealth of a country; in Senegal, production of groundnuts takes almost a quarter of the national GDP (Konate et al., 2022). Outside the economy, the groundnut is a nutritional power fountain as it supplies vital fats, vitamin E and almost half of the daily protein consumption required by most of the rural families (Ojiewo et al., 2020). The average groundnut yield in Africa remains substantially low at 964kg/ha compared to 3500kg/ha for United States and other developed countries (Abady et al, 2019; Bernard et al, 2020). Bernard et al. (2020) attributed the low yields in Africa to poor inputs, low yielding varieties, erratic rains, diseases and aflatoxin which affects Africa export potentials various markets. An empirical study by Mukoye et al. (2019 noted that 75-80% of global groundnut production is controlled by resource poor smallholder farmers in developing countries with yield of 500 to 800kg/ha compared to the potential yield of 2.5t/ha. In the last two decades, over 100 improved groundnut varieties have been introduced to Sub-Saharan Africa for enhanced production (Abady et al. 2019). Nigeria remains the lead producer of groundnut in Africa in the last decade accounting for 3.2 to 4.3 million tons (FAO, 2022). The Nigeria is closely followed by Sudan, Senegal, Tanzania and Chad with average productivity of 2.04, 1.2, 0.95 and 0.88 million tons respectively from 2012 to 2022 (FAO, 2022; Konate et al., 2022). Fig 2.1 and Table 2.1 provide further details of groundnt production trends in Africa between 2012 and 2022.

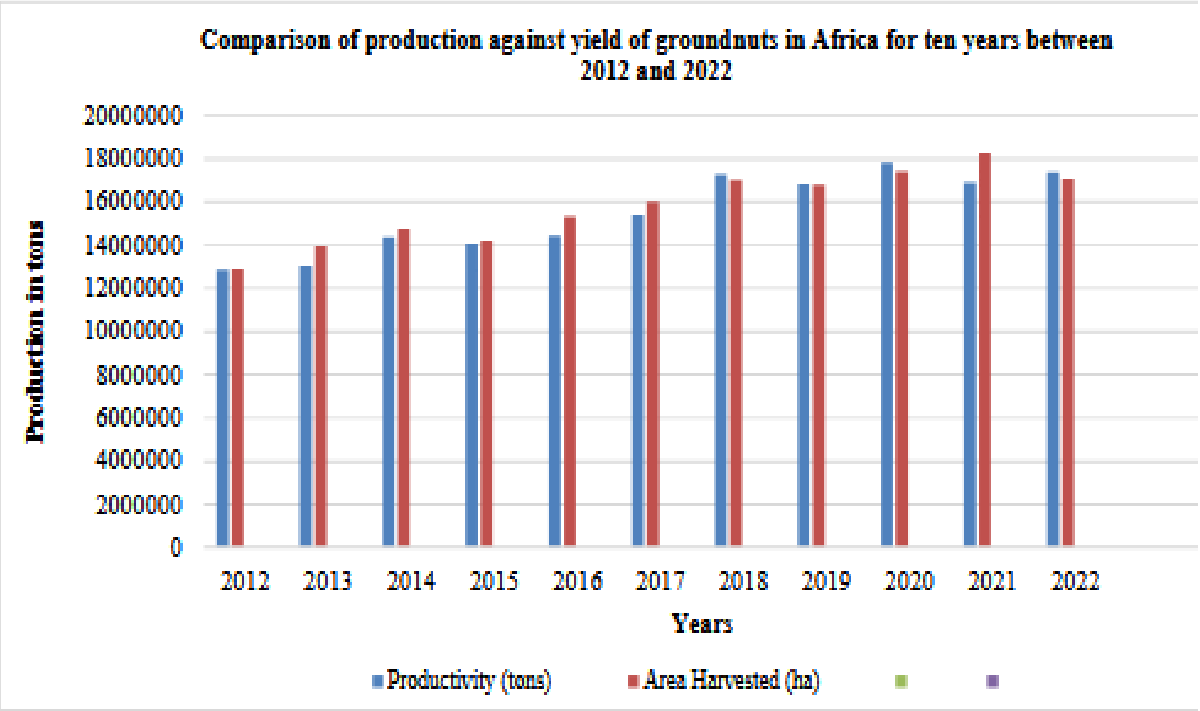

Figure 2.1. Graph showing groundnuts productivity trend in African regions between years 2012 and 2022

(FAO et al., 2022; Konate et al., 2022)

Table 2.1: Top Groundnut Producers in Africa (2012–2022) in Tons

Year	Nigeria	Sudan	Senegal	Tanzania	Chad	Cameroon	Ghana	Burkina Faso	Niger	Congo	Malawi	Kenya
2012	3,313,500	1,032,000	692,572	810,000	1,297,712	633,799	475,056	311,273	291,826	405,277	368,081	24,639
2013	2,474,530	1,767,000	677,456	1,425,000	965,162	635,947	408,814	349,688	342,772	413,342	380,800	94,072
2014	3,399,158	1,871,000	669,329	1,635,335	791,088	578,626	426,280	335,223	403,365	421,568	397,503	56,149
2015	3,467,446	1,042,000	1,050,042	1,835,933	720,138	608,731	417,199	365,887	427,324	422,327	274,876	28,574
2016	4,360,500	1,826,000	719,000	640,000	871,249	601,104	425,825	519,345	453,577	434,694	275,070	10,687
2017	4,521,450	1,648,000	1,405,223	650,000	870,094	595,961	433,772	334,328	461,842	443,388	386,319	19,273
2018	4,600,000	2,884,000	1,500,588	670,000	893,941	664,128	521,032	329,783	594,162	445,476	344,583	21,333
2019	4,346,335	2,828,000	1,421,288	680,000	873,228	725,825	563,000	396,129	543,951	455,356	350,000	15,463
2020	4,230,560	2,773,087	1,797,486	690,000	840,035	801,632	565,000	630,526	593,669	465,474	350,000	15,604
2021	4,227,520	2,355,000	1,677,804	710,000	797,953	500,000	502,000	477,254	518,784	475,817	350,000	12,897
2022	4,284,000	2,500,000	1,501,498	710,000	829,431	500,000	611,000	559,064	670,614	486,389	350,000	11,000

FAO et al., 2022; Konate et al., 2022)

Projection for 2025/26 the marketing year, Africa is a strategic centre with the percentage of global supply of groundnuts reaching nearly one-fourth. Nevertheless, 13.2 million metric tons appear as the estimated output of the continent which denotes a slight contraction because of unpredictable weather and pest pressures in the West African area (USDA, 2025).

But the continental narrative is that of strongly contrasting turns. Whereas there has indeed been an impressive 11.8 percent increase in production in Egypt thanks to increased irrigation and an increase in the quality of seeds, other countries such as Ghana have encountered losses due to the changes in rainfall and the inability to access basic inputs (USDA, 2025). This gap in performance indicates a structural gap between technologically advanced systems based on irrigation and traditional rainfed farming

These are the limitations that should be tackled regarding the future of African food systems. Groundnut is not solely a source of food, but due to its capacity to correct the level of nitrogen in the atmosphere, it forms a base word of the sustainable crop rotation in dry areas. Investment in agricultural research should be an ongoing affair as a way of realizing its potential. Its attention should be drawn towards aflatoxin resistant, high yielding and climate smart varieties. The solution must probably be high-tech and low-tech. Crafting a stronger regional trade by engaging in such regional projects as the African Continental Free Trade Area (AfCFTA) may bring additional opportunities to the market and establishing a digital platform may enable farmers to have real-time access to the weather and price information which they will require to make informed decisions.

2.2.4. Production of Groundnut in Ghana

The groundnut (Arachis hypogaea L.) in the agricultural landscape of Ghana especially in the ecological regions in the north is much more than mere commodity. It serves as a two-tier anchor of rural existence since it serves as both the main source of protein and an essential source of cash revenue (Nboyine et al., 2023; Koomson et al., 2024). The crop which is cultivated mainly by the smallholders on farms that do not intensively cover more than two hectares has a success that is closely connected with the environment. Since these systems are nearly rainfed, the economic survival of millions of people is directly linked to the condition of the soil and seasons.

Examining the five-year-old data, one will notice a curious phenomenon: as the size of the groundnuts allocated land has risen by almost no change in 0.33 million hectares, the resultant harvest saw its highs and lows (USDA-FAS, 2022). The fixed land area implies that even expansion in the industry will have to result in more intensive production, i.e. more and more production with the same amount of land, as opposed to opening more land.

National yields tell a story of resilience and setbacks. After a dip in 2021, the sector saw a significant rebound in 2022/23, with output jumping over 11 percent to 0.47 million metric tons (USDA, 2025). This recovery was largely a result of better rainfall and slight improvements in seed quality. However, the most recent projections from 2025 suggest a coming downturn. National output is expected to slip by about 6.2 percent, a contraction driven not by a loss of land, but by the erratic rainfall and dry spells that have plagued recent cropping cycles (USDA, 2025). This pattern confirms a sobering reality: Ghana’s groundnut production is structurally fragile, and productivity is still largely at the mercy of the weather.

The yield gap in Ghana is still a big challenge. Although in contemporary management it is possible to push the yield to 3.0 mt/h, the national average can scarcely reach half of it. This is not a chance occurrence, it is a result of depending on old local varieties, and the unavailability of better fertilizers and better seeds. To most of the smallholders, the cost of inputs is very high, and they have no credit, which makes modern farming unaffordable to them.

The biological threats also make the situation more complex. The groundnut rosette virus and the leaf spot diseases are diseases that have to be fought at all times by farm owners, but the worst is the aflatoxin contamination. Aspergillus fungi lead to these toxins, which are not only dangerous to the state of plants; they are a health epidemic facing society in connection with liver damage and impaired growth (Kotu et al., 2022). Since the toxins can remain in the field to the market, they effectively restrict Ghanaian farmers to be able to sell their produce to the high-paying markets where the safety requirements are high.

2.3. Sustainable agriculture

Agricultural sustainability is not only the immediate ability to grow food that we are now interested in, but the far reaching transformations that the very ecosystems that support farming undergo. In the quest to achieve high yields, the price to the ecology has been high in most cases over the decades. Intensive application of chemical fertilizers such as the use of nitrates has also caused massive leakage of nutrients, especially nitrates which affect the wellbeing of the soil and water (Craswell, 2021).

The effects of such chemical dependency are extensive and extend to the human health (Nicolopoulou-Stamati et al., 2016) and killing of natural predators since the compounds are non-selective. Most importantly, perhaps, intensive practices have deteriorated the natural capacity of the soil to undergo the complex biological processes that are the foundations of agriculture.

Current agriculture has found itself in a crossroad situation where it must balance the demand of food, fibers, and fuel with total necessity of repairing the environment. Today, it is not the production question, but the question of repairing what is broken: how to restore the resources of soil, ensure the quality of water, and reduce the consequences of a changing climate (Livsey, 2021).

Contrary to the situation with the older models, which accepted the soil as the medium through which the chemicals act, the modern view relies on the smooth combination of the biological, physical and chemical parameters. We have now come to understand that the long-term profit of a farmer is directly proportional to the biological vitality of their land. Sustainable agriculture can thus be described as being characterized by practices that safeguard the environments and the human health and ensuring that economic interests are not compromised to the detriment of the human communities and the animals, at the expense of the short-term economic benefit.

Sustainable agriculture is an intergenerational agreement at the very core. It aims at fulfilling the social and nutritional demands of the current generation without impairing the capacity of the future generation to succeed. This needs a profound realization of ecosystem services natural interactions between organisms and the environment that make life possible (Livsey, 2021).

Agricultural philosophy turning its back on the dependence on external inputs, and turning to the improvement of natural resources. Sustainability is no longer viewed as an added value or even an add-on; it is being factored into the business of being the operating principle of a robust and financially sustainable food system.

In the 1970s, the process of implementing agricultural sustainability was mainly focused on the retention of crop production. During the time, the assessment of the soil quality was primarily attained by determining whether the soils had the capacity to efficiently sustain plant growth. By contrast, the modern-day methods have a more inclusive approach and view soils as multifunctional systems, which are not just productive but also able to provide ecosystem services, resistance to perturbation, and stability throughout the long term (Bünemann et al., 2018). Though such a shift toward a multifunctional interpretation of the agricultural systems is a good conceptual step in the right direction, it also comes with new complications. These obstacles, though, can also be interpreted as the chances to enhance the results of sustainability.

Global greenhouse gas emissions through the release of carbon dioxide (CO_2), methane (CH 4), and nitrous oxide (N 2 O) are largely due to agricultural activities (Lynch et al., 2021). It has been projected that with the existing tendency of intensification of land use and clearing of land, the amount of emissions in terms of CO 2 C equivalents may increase to about 3 Pg/yr by 2050, which is almost an one-third of the current emissions of the fossil fuel (Tilman et al., 2011). However, these emissions can be reduced by up to two-thirds by practices such as adopting sustainable agricultural management adopted with the help of the currently available technologies (Tilman et al., 2011). Such cuts would be a big step toward the constriction of the role of agriculture in climate change.

In addition to emission reductions, there is a growing body of literature showing that agriculture can actively be a solution in reducing climate by also acting as a natural sink to atmospheric carbon. The 4 per mille: Soils for Food Security and Climate is an initiative that aims at raising the amount of organic carbon held in soils by 0.4 percent annually (CGIAR, 2018). This practice can reduce the climate change as well as give yield results, such as soil health (Minasny et al., 2017). The possibility of increased productivity and the minimized impact on the environment is a good argument to use to maximize land and water resources. The need to sustainably use natural resources is further supported by the rising population pressures and heightened competition of non-agricultural areas by land and water (FAO, 2013).

2.4. Why sustainable agriculture?

Modern agriculture has succeeded in producing more food than ever before, but this success has come at a growing cost. Today’s farming systems depend heavily on inorganic fertilisers, pesticides, herbicides, monocropping, mechanised tillage, and large volumes of irrigation water, most of which are closely linked to fossil fuel use (Misra & Ghosh, 2024; Sekhar et al., 2024; Sadiq et al., 2024). While these inputs help boost yields in the short term, their long-term consequences are becoming increasingly visible. Soil fertility is declining, water resources are under pressure, biodiversity is being lost, and agriculture is contributing significantly to greenhouse gas emissions. The growing uncertainty of climate change has demonstrated a fundamental weakness of contemporary agriculture: our excessive dependence on high-input production models. These systemic weaknesses have transformed sustainable agriculture to being a choice to becoming a necessity. Sustainability simply means creating the food, fuel, and fiber the world needs and at the same time preserving the natural resources that enable farming to occur. This strategy takes into consideration the ability of agricultural systems to absorb both climatic and economic shocks by shifting the emphasis on the highest yield and placing it on the long-term resilience of the agricultural systems (Muhie, 2022).

Conventional intensification of merely increasing per unit of land, which was the order of the day, was heralded as the silver bullet in the world hunger problem. Although the enhancement of fertilizer and pesticide application can certainly skyrocket the output in the short run, additional inputs do not necessarily mean the improvement of efficiency (Alborov et al., 2022). Indeed, farmers tend to reach the end of a downward looking curve when these chemicals are used without an equivalent emphasis on the health of the soil or the care of water.

In the given case, the marginal value of a bag of fertilizer decreases with every new bag, which leads to the increase in costs and the leveling off of productivity (Liu et al., 2022; Huerta de Soto, 2024). This puts farmers at the disadvantage of spending a lot to earn little and in the process putting the local environment in an unsustainable position.

The global agricultural community has realized these trade-offs and it has shifted its focus on sustainable intensification. This model aims to boost productivity without a price associated with degradation of the natural environment or destruction of the ecosystem (Cook et al., 2022; Denning, 2025). It recognizes that the triadic food security is more of a three-legged stool: it needs to be high but the high yields must be underpinned by healthy soils and sustainable livelihoods (Tefera et al., 2024).

This, in effect, implies transitioning to integrated land management. Zero tillage, cover cropping and complicated rotations of crops do not just preserve the dirt but also nurture the useful organisms that hold soil structure and do not demand synthetic interference (Țopa et al., 2025).

Moreover, the practices are an effective climate mitigation tool. Due to the fact that sustainable systems trap carbon in the soil and the necessity to convert fewer lands to farming, they create a carbon sink, which helps stabilize the global climate (Srivastava, 2025; Liang et al., 2025).

It is also driven by the ambition of sustainability as a reaction to the mixed history of the Green Revolution. Even though that period has managed to increase food production in the world, the negative effects on the environment have become unavoidable (Ma et al., 2024). One of the current trends is the growing interest in systems that would provide a triple win: food security, environmental recovery, and social well-being (Hegab et al., 2023).

On the international scale, this change is one of the main contributors to the implementation of the Sustainable Development Goals (SDGs), namely the ones aimed at poverty reduction (SDG 1), climate action (SDG 13), and ecosystem protection (SDG 15). Agroforestry, precision farming, or livestock integration all aim to enable farmers to do less and do more with less, and adapt to a changing world which is volatile (Misra & Ghosh, 2024).

Lastly, sustainable agriculture encompasses the concept of protecting the ecosystem services of clean water, productive land, and climate control that do not only provide benefits to the individual farm at an exceptional distance (Rehman et al., 2022). Nevertheless, the change is not risk free. The adoption of these methods by a farmer is usually determined by their perceptions of uncertainty and the intensity of the institutional support they get (Badsar et al., 2023; Ricart et al., 2025). Thus, sustainability cannot be considered an option or a niche strategy, it is the key to the proper basis of a robust and fair world food system.

2.5. The Role of Sustainable Agriculture in Farm Performance and Household welfare

Sustainable agricultural philosophy is based on three pillars which include; environmental health, economic profitability, and social equity. Although these ideals have existed on the global policy agenda, with the introduction of the SDGs in 2015 by the United Nations they have now been placed in the limelight of the global policy agenda. This change is not a mere theoretical excursion but an actual need in Africa. The issue of environmental degradation and the necessity to produce reliably is the stimulating force that is making farmers in the continent move towards the adoption of various forms of sustainable agricultural practices (SAPs).

Interestingly, smallholder farmers are burdened most with the responsibility of undertaking this transition. Although such farmers have few resources, they are estimated to feed about 70% of the world population (Lowder, Skoet, and Raney, 2016). Sustainability to these people is not merely an environmental option, but an essential adjustment strategy employed to help adapt to the increased uncertainty of the shifting climate (Abdulai and Huffman, 2014; Gebremariam and Wünscher, 2016).

The empirical evidence indicates the sustainability practices can be effective forces of both the farm performance and the household welfare. Studies have always indicated that such advantages tend to be cumulative; the more the practices that a farmer adopts, the higher the payoff. To illustrate, Gebremariam and Wünscher (2016) observed that farmers who made an increased trade-off of SAPs realized better net crop incomes and increased household consumption in Ghana.

This was also the same so-called synergy effect witnessed in Zambia as the combination of several sustainable technologies produced a much greater effect on yields and poverty alleviation compared to the sole use of either of the components (Khonje et al., 2018). The tendency applies to a wide range of crops; in the example of Marenya et al. (2020), the more the practices were adopted, the more they yielded maize, and the income.

To its core, sustainable agriculture is concerned with a fragile balance between production and ecosystem well-being (Viñals et al., 2023). With global societies now grappling with the realities of population swellings and shifts in climate, these practices have ceased to be considered as innovative and are instead becoming mandatory (Steenwerth et al., 2014; Rockström et al., 2017). These strategies will enable future and current generations of farmers to enjoy a degree of prosperity and food security that is robust and resilient to the 21st century challenges by preserving the resources of today.

2.6. Theories and Models of Technology Adoption

The adoption of innovation or technology is inextricably linked to decision-making, which is ultimately a cognitive activity (Rogers, 2003). Traditionally, cognitive models and ideas about technology adoption were associated with attitude development and social psychology (Michelsen and Madlener, 2013). Individuals must weigh the predicted benefits of adoption against those of available alternatives before making a firm decision to adopt a technology, innovation, or practice. The fundamental idea is that the advantages of adoption outweigh the potential costs associated with other options. Previous research (Rogers, 2003) has largely explained farmers' adoption behaviour using three paradigms: the innovation-diffusion model, the economic constraint model, and adopter perception models.

2.6.1. Innovation diffusion model

The process of spreading new technologies according to the theory of diffusion of innovation created by Rogers (2003) is described using four main components including innovation-decision process, perceived features of the innovation, the adoption rate, and the innovativeness of individuals. The key concept in this framework is the innovation-decision process that is executed in 5 consecutive steps: knowledge, persuasion, decision, implementation and confirmation. The first level of interaction with biochar that farmers will encounter at knowledge level is a production technology and how it works with possible benefits that it can provide. Despite the technical soundness and cultural acceptability of the technology, the model appreciates that lack of access to information, information asymmetry and high costs of search can limit the use. The availability of timely, correct and complete information is therefore crucial in influencing the adoption decisions of the farmers.

In order to resolve these informational deficiencies, the institutions of research and development take various dissemination channels to transfer knowledge related to biochar to farmers. These are the public agricultural extension services, innovation platforms, lead or model farmers and the extension staff of local non-governmental organizations. When studying the adoption behavior, the degree and the quality of interaction between the farmers and the extension agents becomes of specific concern. In addition to the formal extension channels, the farmers also access the information provided by the mass media through radio, television, and newspapers along with social networks and interpersonal communications. When farmers shift towards persuasion, they consider the technology and make the decision of adopting it or not. The confirmation stage is the next step of this decision and adopters are in need of confidence and confirmation of their decision.

In this context, farmers evaluate emerging technologies in terms of particular qualities that facilitate less uncertainty on the decisions to adopt. According to Rogers (2003), there are five important characteristics of innovation that affect the adoption behavior; relative advantage, compatibility, complexity, trials, and observability (Vagnani and Volpe, 2017). The rate and the degree of adoption are largely dependent on the perceptions of the farmers towards these attributes. Practically, the prospective adopters consider perceived advantages and expenses of the technology. Relative advantage denotes the degree to which a new practice is perceived to be better than standing practices normally in the context of economic returns, social good or in general performance. The concept of compatibility is used to describe the extent to which the innovation is compatible with current values and experiences of farmers as well as their farming practices, hence affecting its acceptability and adoption.

2.6.2. Unified Theory of Acceptance and Use of Technology (UTAUT)

One of the most popular theories that have been developed by Venkatesh, et al. (2003) and extended by Paolo Muccioli, et al. (2016) is the Unified Theory of Acceptance and Use of Technology (UTAUT), which facilitated our comprehension of the reasons why individuals adopt or do not adopt new innovations. Despite its solid foundations in the corporate and managerial sphere, an emerging body of literature is proving that the framework proves to be astonishing in its ability to de-escalate the mysteries of rural development. Nowadays, researchers are increasingly resorting to the concept of UTAUT as the means of explaining the unique motives that can influence a farmer into embracing sustainable but frequently demanding farming technologies.

The peculiar feature of UTAUT is its integrative, holistic nature. It does not simply consider only one lens, but it is a combination of knowledge of various heavy weights of behavioral science such as the Technology Acceptance Model, the Theory of Diffusion of Innovation, and the Social Cognitive Theory. Combining all these different views into a single integrated concept UTAUT provides a far more in-depth analysis into the human psyche than its predecessors did. Empirical evidence indicates that the synthesis has a great enhancing effect on its power to explain so that the researchers can explain a large percentage of the variance in the actual use of technology (Venkatesh et al., 2003).

This framework of adoption lays down the story of adoption on four main pillars. The former is the performance expectancy, which is in fact a perceived utility measure. This is translated to a very basic yet crucial question in the mind of a farmer: Will this tool help in making my life better? Is it hoped to boost production, reduce production costs or save the environment, adoption can only pick up ground when the technology has clear, tangible payoffs, which are felt to benefit the livelihood of the farmer.

What UTAUT really has to offer is, however, the fact that it recognizes that there is no two farmers like it. The theory allows consideration of moderating variables such as age, gender, and experience to make it clear why a mature farmer may respond to innovation in a different way compared to a younger farmer (Chang, 2012). Such flexibility has enabled the framework to be effectively transferred to other cultural and geographical locations. In other countries such as Vietnam, these constructs have been employed in recent studies by Nguyen et al. (2023) to demonstrate that institutional support and social pressure have a direct impact on adoption of precision agriculture. Finally, UTAUT is a strong and versatile roadmap to the challenging complexities of agricultural innovation that can enable us to comprehend why a new tool may be considered a breakthrough by some farmers and a risk to others.

2.6.3. Technology Acceptance Model (TAM)

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2.6.4. The expected utility theory

According to economic theory, the anticipated utility theory is the most prominent theory in adoption studies. According to Caswell et al. (2001), in economics, the adoption of a new technology is based on the assumption that the individual is a utility maximizer who makes a decision based on maximising his or her expected utility, subject to policies, natural resource assets, personal characteristics, and prices. These researchers related smallholder farmers' decisions to their decision to engage in a business, implying that it may have a high initial cost but a pool of advantages over time. As a result, an individual's decision to adopt a new technology may vary over time as they interact with others who have already adopted the technology.

2.7 Concept of Biochar

Biochar is at first sight like the common charcoal, a dark, carbon-rich, and porous substance. Nevertheless, its most remarkable benefit is that it is created by using the method of pyrolysis, a complex thermochemical reaction during which the organic biomass undergoes high temperatures in a place with little to no oxygen (Xie et al., 2022). The result of this process is a material with physical and biological properties that are far beyond fuel. Through its capacity to play the role of linking waste management with climate action, biochar has ceased to be a fringe agricultural amendment, but a key participant in the quest of the United Nations Sustainable Development Goals.

Although technically, biochar is a byproduct of biomass processing, its use in the environment is extensive. The most important aspect of it in the 21st century is that it has the capability to sequester carbon, in other words, to introduce it irreversibly into the soil over centuries instead of it being released into the atmosphere as greenhouse gases (Afshar & Mofatteh, 2024). This renders it a powerful instrument of developing climate resilience, since it is both a way of capturing carbon in the atmosphere, and revitalizing desiccated or nutrient deprived terrain. As part of farming systems, biochar has been proven to have an impressive capacity to enhance fertility, moisture retention, and suppress soil-based emissions and, thus, roots the principles of a circular bioeconomy.

The great number of organic substances commonly known as lignocellulosic biomass available as feedstock results in the versatility of biochar production. We produce 200 billion metric tonnes of agricultural residues each year globally in the form of rice husks, wheat straw, sugarcane bagasse, coffee hulls, and others (He et al., 2022; Zhao et al., 2022). These feeds are lignin and cellulose and hemicellulose-rich that supply the structural bones of the resultant biochar (Supraja et al., 2023). Repurposing such residues helps us escape environmental risks that can arise due to open-field burning and landfill dumping and transforms so-called waste into a regenerative resource (Koul et al., 2022).

This last character of any biochar, namely its internal structure of pores, its total surface area, and its ability to serve as a reservoir of nutrients, is not an accidental finding. Instead, it is an immediate by-product of the thermochemical path, which the biomass follows in the production process. The conversion is typically done in three different technical directions, such as slow pyrolysis, fast pyrolysis, and gasification (Wang et al., 2020). Both of these approaches manipulate heat and time in different ways and this leads to products that are used to serve incredibly diverse environmental and industrial purposes.

The so-called slow pyrolysis is considered the king of the gold standard of agricultural soil restoration. This process deliberately favors the solid yield by heating organic matter at a controlled rate that usually remains within a comfortable range of 300 o C to 500 o C. With this slow cooking method, the biomass is able to maintain a stable carbon skeleton forming a biochar that is specifically optimized as a soil amendment. Although the major objective is the solid char, the process is resource-efficient because bio-oil and syngas are captured simultaneously, and they may be collected as the secondary streams of energy (Zakaria et al., 2023; Lee et al., 2020).

The fast pyrolysis process, on the other hand, is based on totally different logic. In this case, the biomass undergoes a high-temperature shock, much exceeding 500 o C within seconds. This approach is essentially an energy-based approach; its primary goal is to ensure the maximization of liquid bio-oil production. It is not without biochar as a byproduct, but the solid that comes out is usually less voluminous and structurally dissimilar to the one produced by slow-pyrolysis. The resulting liquid fraction is valued due to its great energy density, where the effectiveness with which the feedstock can be transformed into fuel producing services as either a soil-builder or an industrial fuel hinges on a change in the pace of heating (Tan et al., 2021; Makepa et al., 2023).

Although its potential as a pollution control tool and sustainable remediation is immense, there are no stones along the way to large-scale adoption. In order to proceed, several major limitations have to be overcome by researchers and policymakers. The logistical issue of the persistent and quality supply of feedstock is one of the key bottlenecks (Al Masud et al., 2023). Moreover, the economic and environmental benefits of pyrolysis are sometimes compromised by the high energy demands of the process, as well as the expenses of transportation of large-sized materials (Meng et al., 2020; Torres-Morales et al., 2023). Scientific questions are also unanswered to a great extent on how biochar ages in the soil over decades and how it interacts with different communities of microbes in the long run.

2.7.1. Impact of biochar application on crop productivity

Biochar implementation into agricultural systems does not merely enrich their soils with nutrients, but it is a complete redesign of the soil environment that predisposes it to greater crop yields. Biochar enhances the fertility of the soil by increasing the soil organic carbon level and changing the physical architecture of the earth, making it more welcoming to plants growing in it (Oni et al., 2019; Tomczyk et al., 2020). This enhancement of soil quality is more or less the reinforcement of the natural defenses of a plant, which is more resistant to the realities of the world in terms of biotic and abiotic stressors (Yeboah et al., 2020). This is the ultimate synergy between better tolerance of plants and better health of soil, which leads to the steady growth of yields in sustainable systems (Jeffery et al., 2017).

The studies by Sahota et al. (2018) also indicate that biochar is a triple-threat amendment, as it stabilizes carbon sequestration, restores the quality of the soil, and directly promotes crop production. Biochar impact is most transformative in nutrient-depleted or degraded landscapes, where it serves as a remedial force to make it agricultural once more (Hussain et al., 2017).

In addition to the mere physical alterations, it seems that biochar also seems to regulate the physiological functioning of the actual plants. How much of these advantages are to be obtained, though, is frequently a matter of the origin of the biochar and the application rate. As an example, a comparative study of biochar made out of rice straw and corn stalks was carried out in Northern China by Yang et al. (2015). Their results also showed that rice straw biochar was especially efficient in enhancing the yield of corn, peanuts, and winter wheat. The experiment also showed a very strong dose-response curve: with small doses of 1 or 2 tonnes per hectare, a 5 percent to 15 percent increase was realized, but doubling the dosage to 4 tonnes per hectare increased the benefits of the dose-response by up to 20 percent. On the same note, Van Zwieten et al. (2010) demonstrated that adding 10 t/ha of paper mill biochar increased wheat seed germination rates. Furthermore, Joseph et al. (2015) discovered that a biochar derived from acacia wood coupled with clay, chicken litter, and minerals improved wheat growth at a low dose (100 kg/ha).

In a similar field experiment conducted in Ayuom, a farming village located in the Ashanti Region, Dugan (2012) investigated the impact of charcoal and charred maize stover on production of maize. The findings established that the amendments using charcoal and maize stover biochar had significant effects on the yield of cob and grain. In particular, the use of charcoal enhanced the results of maize grain production by a significant margin ($p = 0.002$), namely, 4.43 t/ha to 4.93 t/ha, which is a 17.8 percent improvement. On the same note, addition of burned maize stover also demonstrated a statistically significant increase in yield ($p = 0.020$), which led to the increase of the grain products to 4.71 t/ha.

Akom et al. (2015) also offer additional evidence by evaluating the joint impact of biochar and inorganic fertilizers on the production of yams in a forest agro-ecological system in Ghana. The researchers used wood-shaving biochar at the rate of 0, 5, 10, and 15 t/ha in combination with various inorganic fertilizer treatments using Ferric Acrisol. Although both biochar and inorganic fertilizers did not have any notable impact on the vegetative growth of plants used as indicators of yam, the application of biochar had a significant effect of increasing the numbers of seed yams per acre ($p = 0.05$). The research concluded that biochar can be used to sustain the production of the yam especially in regard to the generation of planting materials.

On the same note, Konamah-Yeboah (2015) examined the effect of biochar amendments on the growth and yield of onion (Allium cepa) in Agroforestry Research Farm at the Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology (KNUST). These findings demonstrated that the biochar-treated soils made significant differences ($p = 0.05$) on the height of the plants with the highest rate of biochar application (39 t/ha) yielding the tallest plants (18.48 cm) at the end of the twelfth week of planting. It was then succeeded with the control plot (10.42 cm), 26 t/ha treatment (9.64 cm) and 13 t/ha treatment (8.84 cm). Conversely, the diameter of the bulbs, bulb weight and the yield of the dry matter were significantly and consistently greater under all the biochar-amended plots than the control. The maximum biochar rate brought about growth rates of 163.2 percent in bulb diameter, 179.4 percent in bulb weight and 205.37 percent in dry matter yield, compared to the placebo plots. More recently, Frimpong et al. (2021) demonstrated that the combined application of biochar, NPK fertilizer, and compost significantly enhances key soil fertility indicators, including soil organic carbon, total nitrogen and phosphorus, exchangeable acidity, and cation exchange capacity. Improvements in these soil properties were found to translate into better soil fertility and increased crop productivity.

2.7.2 Economic potential of biochar for farmers

Within the changing field of sustainable development, biochar has been shifting its role of a mere environmental concern to a commodity that is highly priced and has deep ecological and economic impacts on the energy sector and the agricultural industry. Its strength to support the bottom line of a farmer lies in its twofold capability to increase crop productivity and provide protection against the unpredictability of the biological and environmental stressors (Oni et al., 2019; Semida et al., 2019). By providing the ability to provide stable revenue potential amidst such difficulties, biochar is providing a type of biological insurance that has rendered it a strong investment to consider in the present-day grower.

The short term financial benefit of using biochar is one of the most obvious ones as the overhead costs (mainly water and fertilizer costs) are cut drastically. As an example, Kroeger et al. (2021) found that biochar-treated soil needed about 37% of the irrigating water that would represent a huge water-savings potential in the water-deprived areas. Moreover, the biochar efficiency in terms of nutrient delivery will be greatly improved when it is combined with fertilization measures. A study done by Zheng et al. (2017) showed that biochar-compound fertilizers enhanced the use efficiency of nitrogen by 43.1, and eventually increased net income by 12% over the conventional inorganic fertilizers.

The economic importance of biochar can be thought to be more truthful in long-term advantages on soil carbon and residue administration. Although short-term yield improvements may not seem very impressive at times, the durability of the material guarantees long-term benefits in decades. Aller et al. (2018) underlined that this approach delivered optimal carbon levels at the rate of 22 mg/ha, which both spiked carbon levels but provided a 50 percent reduction in maize residue demands in a 32-year perspective. The Net Present Value (NPV) calculations substantiate this long-game view with a current cost being offset by total gains in the future. In their studies, Dickinson et al. (2015) discovered that the positive impact of single biochar application in cereal cropping system may last up to 30 years, thus a good intergenerational investment in the farm.

Mohammadi et al. (2017) in their study on rice systems showed that addition of 18mg/ha resulted in a 12 percent increase in NPV and a reduction of traditional energy production costs by 27 percent after eight years. Most noticeably, however, with the maturity of carbon markets, the financial benefit of biochar is even more dramatic. In cases of high-carbon-prices, the greenhouse-gas abatement can cause the shift in the value variations of NPV by up to 71.

2.7.3 The willingness of farm households to adopt new technologies

Over the past years, the influx of new agricultural technologies has given a promising pathway of enhancing the productivity and the resilience of smallholder farmers. The success of such innovations, however, remains purely dependent on how much households are willing to incorporate them into their traditional systems, which, in Ghana, is particularly complicated through small-scale farming as the main substantia of the rural way of life. Studies indicate that this decision making process is hardly a straightforward calculation but a complex experience that is through the urge to have improved livelihoods and also an awareness of the risks that may be presented. Indicatively, Ragasa et al. (2019) noted that Ghanaian farmers are much better inclined to adopt new ways when they feel that there is a visible direction to the growth of their household incomes. However, financial incentive is inadequate, it has to be accompanied by easy access to pertinent reliable information that is provided with extension services, training programs and the priceless knowledge sharing amongst neighbors.

Technology adoption is also a strong screen of the social and demographic structure of a household. Education, size of farms and family makeup, have been identified to be decisive in different regional settings. Kassa and Abdi (2022) mentioned that in Southern Ethiopia, the adoption was determined by the proximity of the farmer to the land and his or her own views regarding climate variability. Likewise, in Mali, Sanogo et al. (2023) found that age, gender, and belonging to the local cooperatives formed different tendencies in the use of climate-smart technologies. These observations demonstrate that the process of adoption is not a homogenous entity but rather entrenched into the social and economic realities of every family.

Another crucial support in this transition is the institutional and policy-related one. Based on the Behavioral Reasoning Theory, Feng and Zailani (2025) showed that governmental endorsements and the persuasion of an opinion leader in the community can substantially change the willingness to pay on the part of a farmer to acquire novel tools. This observation is replicated by Sisay et al. (2023), who discovered that those households that had better access to credit and formal climate information had higher chances of making the transition to modern farming. Their results propose interventions that are highly focused that take into consideration the needs of various groups, including low-income families or those with less access to formal education to make the adoption of technology inclusive, as opposed to exclusionary.

The most effective change facilitators have always been training and knowledge sharing that are led by peers. As Ferrer et al. (2023) emphasized, although formal training is vital, the opinion of the fellow farmers and previous experience of a grower has a higher priority in the industry. Interestingly, their work also proposed that house-hold labor dynamics including availability of number of male laborers can create unforeseen opposition to continuous adoption which includes that house-hold structures of a family can sometime hasten or snail down the incorporation of novel practices.

The choice to modernize a farm is eventually influenced by intricate net of economic incentives, institutional trust and peculiar land characteristics. As Cui et al. (2022) revealed, the awareness of the benefits of a technology by a farmer should consider the particulars of the land and the current planting preferences. It is through this holistic vision of adoption that one can conceptualize a form of extension program and policy that extends beyond merely supporting farmers with tools so that they can create more sustainable and resilient futures; a type of policy that will provide the confidence and structural support that the small holder farmers will need to effect change.

2.7. Commercialization of Smallholder Farming

The commercialization of the smallholder farming has become an important engine of economic transformation in the emerging rural development environment. This is not only about selling more crops, but rather, a radical change in thinking and practice, that is, the shift of subsistence-based model to one where market signals and price fluctuations as well as the demand of the consumer dictate production (Do and Nguyen, 2024). The shift is found on a very broad spectrum, which is between the rare sale of the harvest surpluses to complete merging of the farm into market-based systems (Schulte et al., 2023). It is important to note though that the advantages of this change are not automatic most of the time. Trade benefits are annoyingly disproportionate without a strong institutional support.

To most rural families, entering the market place is considered one of the main ways out of generational poverty. Market participation is able to considerably support the standard of living of a household by bringing about the liquid cash and enabling the accumulation of productive assets (Schulte et al., 2023). Nevertheless, there is a gap in the welfare that cannot be closed, namely, the higher income does not necessarily contribute right away to the improvement of health, education, or nutrition of the family. This insinuates that as commercialization enhances the financial aspect of life, it must be accompanied with government investments in social amenities to get maximum benefit out of it in terms of human lives.

The increased market participation can ignite a virtuous cycle among the resource constrained farmers. The result of increased sales is an increase in incomes, and this enables farmers to invest in better seeds or technology, which ultimately increases food security and resilience of the farms (Mutea et al., 2025). Macrolevelwise, such a change will lead to an improved national food system, which favors regional specialization, guided by comparative advantages (Dureti et al., 2023). This in theory enables the whole farming industry to attain economies of scale, which enhance food supply and long-term development.

The way to the market is sometimes obstructed to the average smallholder, despite the obvious theoretical advantages. A large amount of literature emphasizes the presence of a competitive disadvantage of such producers because of the absence of marketing knowledge and real-time information (Meemken and Bellemare, 2020). The external failures contribute to these internal failures: the rotting infrastructure in the countryside, the absence of cold storage, the prohibitive cost of transportation. Farmers may usually withdraw into informal barter networks when the cost of access to the market is too high, turning them even more isolated by the rest of the economy (Ali et al., 2021).

The success of a farmer's commercial journey is also dictated by their personal and social context. Factors such as education level, gender, age, and access to credit determine who can take risks and who cannot (Zondi et al., 2022). Small land sizes and insecure tenure further discourage long-term investment, while the lack of policy support for indigenous or "orphan" crops often leaves smallholders with fewer market opportunities (Hlatshwayo et al., 2021).

2.7. Impact of agricultural commercialisation

Despite the well-established link between agricultural commercialisation, economic growth, and food production, there is evidence that the commercialization of small-scale agriculture is positively connected with the food security of commercialised farming households. For example, Madududu et al. (2021) found that food security in commercialized families is positively connected with the commercialization of food crops (maize, cotton, groundnuts, sorghum, and cowpeas). While food insecurity was included in the Multidimensional Poverty Index, Isinika et al. (2020) discovered that commercialisation of rice was associated with a drop in it in Tanzania; nonetheless, a third of the most commercialised farmers were still multidimensionally disadvantaged.

Ogutu et al. (2020) concluded that commercialisation improved nutrition security in Kenya (as assessed by calories, zinc, and iron intake): income from commercial agriculture increased consumption of purchased foods while not affecting consumption of own farm goods. Income gains from agricultural commercialisation have also been documented, most notably in Zimbabwe (Mahofa et al., 2022). The study's authors therefore reach the following conclusion: "National development strategies that aim to improve food security and reduce hunger at the household level should focus on improving the efficiency of staple food markets to incentivize cash crop commercialisation in smallholder agriculture."

Cazzuffi et al. (2020) discovered that, whereas smallholder commercialization was positively connected with income gain, it was negatively associated with per capita food intake. A recent mixed-methods study by Dzanku et al. (2021) comparing smallholder commercialisation in Northern and Southern Ghana found that there was no overall positive association between commercialisation rates and food security; additionally, cases of so-called "distress push commercialisation" among female farmers, i.e., commercialization driven by necessity, had negative food security implications in Ghana (Dzanku et al., 2021). Farmers in Tanzania with the highest commercialization index also had the highest Multidimensional Poverty Index scores (Aida et al., 2022). Prügl et al. (2021) stated in their case studies of Ghana and Cambodia that the findings "caution us against expecting an unproblematic association of commercialisation with food security." According to Prrügl, et al. (2021), "People living contemporary transitions in rural areas must deal with overcommercialization, income insecurity, and price volatility."

A substantial rice commercialisation program in Uganda had the unintended result of reducing women's empowerment as men took up responsibility for agricultural revenue (Ntakyo & van den Berg, 2022). Dzanku (2022) discovered similar results in a large panel study conducted in

Ghana, where the commercialisation of cocoa and oil palm resulted in a concentration of income and decision-making authority in the hands of men, despite the fact that nearly half of farm households continued to experience seasonal food insecurity despite high levels of commercialisation. According to a study by van Asselt & Useche (2022) on smallholder commercialisation in Guatemala, there was a negative correlation between female plot management and higher commercialisation. The same study came to the following conclusion: "A policy promoting commercialisation may not be the most effective if the government's priority is addressing farm household nutrition (van Asselt & Useche, 2022)."

2.8. The Sustainable Livelihood Framework (SLF)

The Sustainable Livelihood Framework (SLF) posits that households differ in their levels of asset ownership, capabilities, and exposure to institutional and policy environments, and that the interaction of these factors shapes livelihood decisions and resulting welfare outcomes.

One of the most popular theories that have been developed by Venkatesh, et al. (2003) and extended by Paolo Muccioli, et al. (2016) is the Unified Theory of Acceptance and Use of Technology (UTAUT), which facilitated our comprehension of the reasons why individuals adopt or do not adopt new innovations. Despite its solid foundations in the corporate and managerial sphere, an emerging body of literature is proving that the framework proves to be astonishing in its ability to de-escalate the mysteries of rural development. Nowadays, researchers are increasingly resorting to the concept of UTAUT as the means of explaining the unique motives that can influence a farmer into embracing sustainable but frequently demanding farming technologies.

The peculiar feature of UTAUT is its integrative, holistic nature. It does not simply consider only one lens, but it is a combination of knowledge of various heavy weights of behavioral science such as the Technology Acceptance Model, the Theory of Diffusion of Innovation, and the Social Cognitive Theory. Combining all these different views into a single integrated concept UTAUT provides a far more in-depth analysis into the human psyche than its predecessors did. Empirical evidence indicates that the synthesis has a great enhancing effect on its power to explain so that the researchers can explain a large percentage of the variance in the actual use of technology (Venkatesh et al., 2003).

This framework of adoption lays down the story of adoption on four main pillars. The former is the performance expectancy, which is in fact a perceived utility measure. This is translated to a very basic yet crucial question in the mind of a farmer: Will this tool help in making my life better? Is it hoped to boost production, reduce production costs or save the environment, adoption can only pick up ground when the technology has clear, tangible payoffs, which are felt to benefit the livelihood of the farmer.

What UTAUT really has to offer is, however, the fact that it recognizes that there is no two farmers like it. The theory allows consideration of moderating variables such as age, gender, and experience to make it clear why a mature farmer may respond to innovation in a different way compared to a younger farmer (Chang, 2012). The flexibility has enabled the framework to be incorporated effectively in other cultural and geographical settings. In other countries such as Vietnam, these constructs have been employed in recent studies by Nguyen et al. (2023) to demonstrate that institutional support and social pressure have a direct impact on adoption of precision agriculture. Finally, UTAUT is a strong and versatile roadmap to the challenging complexities of agricultural innovation that can enable us to comprehend why a new tool may be considered a breakthrough by some farmers and a risk to others.

Livelihood assets interact with institutions, influencing households' adaptive ability and well-being. Formal and informal institutions have a significant impact on household innovation uptake and livelihoods. Their effect can be facilitating or inhibiting. They would influence innovation by making markets, labor, and credit more accessible. They can also influence household preferences by shaping ideas and values, which in turn influence production, marketing, and consumption choices (Beuchelt and Badstue, 2013). Other major factors influencing farmers' decisions to adopt climate-smart innovations include farmer heterogeneity in terms of the advantages and costs of the innovations (Tesfaye, 2019). Assessing the factors that would influence farm households to use biochar is therefore grounded in the above theories. Specifically, this study is guided by the Sustainable Livelihood Framework.

2.9. Methodological Approaches to Assessing Technology/Innovation Adoption

Broadly, various statistical techniques have been employed to analyze adoption of agricultural technologies. These techniques include; Regression Models for Multiple Choices (e.g. Multivariate regression models, Multinomial regression models), Ordinary Least Squares (OLS), discrete choice models (Probit and Logit models), Linear Probability model (LPM) among others.

2.9.1 Regression Models for Multiple Choices

These models are appropriate for scenarios that involve many interdependent, independent, mutually exclusive, or ordered decisions. They consist of multinomial regression models, multivariate regression models, and ordered regression models. They have traditionally been employed to analyze categorical or multiple-choice dependent variables with numerous outcomes. Multinomial regression models are used for discrete variables with more than two uncorrelated and mutually exclusive categories; multivariate regression models are used for discrete variables with more than two correlated categories (Chib and Greenberg, 1998). Ordered regression models, on the other hand, work best for finite and ordinal discrete categories (Wooldridge, 2002; Maddala, 1983).

2.9.2. Multivariate Probit Regression Model

For joint adoption of multiple technologies, as in the case of this present study, the multivariate probit regression model is the most suitable strategic model to employ. The Multivariate Probit Model (MVP) has established itself as a cornerstone of modern agricultural economics, specifically when researchers need to untangle the messy, interconnected world of technology adoption. Unlike traditional models that look at decisions in isolation, the MVP recognizes that a farmer's choice to use one tool such as biochar is rarely independent of their decision to use another, like improved seed varieties or irrigation. At its core, this method evaluates the linear relationships between multiple independent predictors and several dependent responses simultaneously (Xu & Craig, 2010; Chib & Greenberg, 1998).

The true statistical "magic" of the MVP lies in its treatment of the error terms through the correlation coefficient, known as rho. In the real world, many unobserved factors influence a farmer's choices. By accommodating correlated error terms, the MVP reveals whether different technologies act as complements or substitutes. This is determined by the sign of the rho coefficient; a significant coefficient tells us that the technologies are linked, and that using separate, simple binary models would lead to biased or inconsistent results.

As Zanre (2024) points out, the MVP moves beyond surface-level statistics to offer a nuanced perspective. If the rho coefficient is negative, it suggests the technologies are complementary—they work better together, much like biochar and organic fertilizer. Conversely, a positive sign indicates they are substitutes, where the adoption of one likely replaces the need for the other. By accounting for these hidden interdependencies, the MVP allows us to see how economic incentives and policy environments collectively ripple through a farmer's decision-making process, providing a much more accurate reflection of life on the farm than traditional models (Sánchez-Cañizares et al., 2022).

This capability is indispensable when examining the adoption of CSA practices, where decisions are rarely made in isolation. For instance, the choice to adopt improved soil and water management techniques may be closely linked with the use of shade tree management, a relationship that MVP can aptly capture and analyse (Negera et al., 2022). Unlike multinomial models, multivariate regression does not adhere to the assumption of the independence of irrelevant alternatives (Choo & Mokhtarian, 2008).

Some recent studies that employed multivariate probit analysis include Danso-Abbeam and Baiyegunhi (2017) and Ahmed (2015). Danso-Abbeam and Baiyegunhi (2017) employed multivariate probit (MVP) and tobit models to explore smallholder cocoa farmers' adoption decisions of agrochemical inputs in the Ghanaian cocoa industry using farm-level data collected from a sample of 838 farm households in four cocoa-producing regions. The result of the study showed that agrochemical management practices are complementary, and thus the adoption of an agrochemical input is conditional on the adoption of other inputs. Different household characteristics, household assets, institutional variables, and the perception of soil fertility status and the incidence of pests and diseases influenced the adoption of individual agrochemical inputs. The results also showed that the intensity (or extent) of agrochemical adoption (measured as farmers' expenditure on agrochemicals) is also influenced by some socioeconomic and institutional variables, such as extension services and farmers' visits to demonstration farms. Ahmed (2015) also examined the nature of the relationship that exists between two broad categories of intensive and natural resource management by using fertiliser and certified seeds as input-intensive technologies and manure and soil conservation as natural resource management practices.

2.9.3. Ordinary Least Squares Technique (Linear Regression)

When establishing a relationship between a continuous dependent variable and independent variables), the most suitable technique is Ordinary Least Squares (OLS), provided that all assumptions are met (Allen, 1994). The linear regression model utilizes the OLS technique to estimate continuous variables when all Gauss-Markov assumptions are met. The OLS estimator aims to minimize the error term to produce unbiased, consistent, and efficient estimates. However, in cases of inter-dependency between the error term and independent variables, the OLS estimator may deviate from optimality. According to Lang (2013), the OLS technique includes both simple linear and multiple linear regressions and is employed when the dependent variable is continuous, allowing for hypothesis testing and interpretation of relationships between variables.

2.9.4. Linear Probability Model (LPM)

In the realm of statistical modeling, the choice of a framework is dictated by the nature of the outcome being measured. When a researcher is faced with a dichotomous dependent variable meaning the response is a simple "yes" or "no," such as a farmer's decision to adopt biochar standard linear regression becomes mathematically unsuitable. In these instances, scholars typically turn to the Linear Probability Model (LPM) or binary models like Probit and Logit to capture the dynamics of technology adoption (Hailu et al., 2020; Scarpato et al., 2017).

The Linear Probability Model (LPM) attempts to bridge the gap by applying the familiar Ordinary Least Squares (OLS) technique to these binary choices. Within this framework, the resulting coefficients are interpreted directly as probabilities, creating a straightforward linear relationship between the predictors and the outcome (Amemiya, 1981; Maddala, 1983). While this simplicity is attractive, the LPM is hindered by two significant structural flaws that often make Probit or Logit the superior choices.

First, the LPM suffers from a lack of mathematical boundaries; because it is a straight line, it can predict probabilities that fall outside the logical zero-to-one interval, yielding nonsensical results like a "110% chance" of adoption. Second, the model assumes "constant marginal effects," meaning it suggests that the impact of a variable such as a $100 increase in income stays exactly the same regardless of whether a farmer is extremely poor or already wealthy (Maddala, 1983). Because real-world behavior is rarely linear, binary Probit or Logit models are generally preferred for their ability to constrain results within a realistic probability curve.

2.9.5. Probit and Logit Models

In contrast to the structural limitations of the Linear Probability Model (LPM) which often struggles with the logical boundaries of "zero" outcomes the standard Probit and Logit models offer a more statistically sound approach. By utilizing Maximum Likelihood Estimation (MLE) rather than the more rigid Ordinary Least Squares (OLS) method, these models can effectively manage binary choices without generating the nonsensical results that plague the LPM.

The primary distinction between the Probit and Logit frameworks lies in their underlying mathematical distributions. The Probit model operates on a standard normal distribution, while the Logit model is built upon a logistic distribution. Despite this technical difference, both serve a critical purpose: they ensure that every predicted probability is anchored strictly within the 0 to 1 interval. Furthermore, they allow for "non-constant marginal effects," acknowledging that a change in an independent variable—like a farmer’s education level might have a more profound impact on someone who is undecided compared to someone who has already made a firm choice (Wooldridge, 2002; Maddala, 1983).

For researchers focused on the adoption of modern agricultural tools, the Logit model is often the preferred path. Its popularity stems partly from its computational simplicity the logistic function is generally easier to handle than the normal cumulative distribution (Amemiya, 1981). Perhaps even more importantly, Logit results can be elegantly transformed into odds ratios. This allows for a much more intuitive interpretation of the data, as it describes the likelihood of adoption in terms that are easier for policymakers to grasp (Maddala, 1983).

The utility of these binary models is well-documented in agricultural literature (Teklewold et al., 2013; Uddin et al., 2014). For instance, Akudugu et al. (2012) utilized the Logit model to peel back the layers of decision-making among farmers in Ghana's Bawku West district. By analyzing 300 households, they demonstrated how specific socio-economic factors dictated whether a farmer would embrace modern technology or stick with traditional methods. This legacy of research proves that when we are trying to understand a simple "yes" or "no" decision in the field, these models remain the most robust tools in our analytical kit.

In the study, technology adoption was defined as binary, thus, those who engaged in modern agricultural production technologies (known as the adopters) and those who did not (known as non-adopters). Again, Uddin et al. (2014) studied the factors affecting farmers’ adaptation strategies to environmental degradation and climate change effects in Bangladesh. They used the randomised lottery method to select 100 farmers, and the data was estimated using a logit model. The dependent variable in the logit/probit model is dichotomous and can only assume two outcome values, i.e., adopt or not to adopt. The major shortfall of the probit/logit models is that they do not cater for intermediaries, hence the need for ordered probit/logit models, which are applied to cases of more than two outcomes. of an ordinal dependent variable (a dependent variable for which the potential values have a natural ordering, as in poor, fair, good, and excellent adoption).

2.10. Factors influencing biochar adoption

Empirical studies have identified common determinants influencing the probability that smallholder farmers will adopt biochar. Within the farm technology adoption literature, it has been shown that multifaceted factors influence biochar adoption. For example, according to research conducted by Osei-Adu et al. (2015), farmers in four key agro-ecological zones of the country reported that only 25% of respondents, the majority of whom had participated in on-farm trials with biochar, were aware of the product and its potential benefits. However, the majority of them believe it has the ability to improve soil conditions, particularly fertility, resulting in increased crop yields. When assessing the potential for adoption and use among farmers in the Ejura Sekyedumase area, the results of a conditional logit analysis show that residential status, farming experience, membership in a farmer-based organisation (FBO), and household size may influence farmers' willingness to adopt biochar technology. Natives, farmers with more years of experience, and small households were most likely to adopt the biochar technology compared to migrants, farmers with less farming experience, and large households. Members with FBO's were also found to be less willing to adopt the biochar technology since their focus was more on access to credit than on improved soil technologies. The technology was found to have a high rate of adoption if farmers were made aware of its potential benefits when applied as a soil amendment. Promoting it with organic manure was also found to be advantageous. There is therefore a need for intensive awareness of the technology, its uses, and its benefits as a soil amendment (Osei-Adu et al., 2015). Additionally, Kibue (2018) discovered that farmer-specific characteristics correlate positively with the adoption of biochar technologies. Farmers with more education are better able to assess the value of new technologies. Farmers with off-farm income are likely to be better equipped to invest in technology than impoverished farmers. Farmers with larger farm sizes are more likely to adopt biochar technology than farmers with smaller farms because they may devote sections of their property to testing the innovation. Because smallholder farmers typically lack the funds to invest in new innovations, the availability of finance will stimulate technological adoption. Farmers receiving extension services, those attending on-farm demonstrations of new technologies, seminars, and workshops, and farmers having positive attitudes towards gathering information and a high frequency of contact with information sources are also expected to adopt biochar. Lastly, if farmers consider the innovation beneficial and are perceptive about climate change, they are likely to adopt it. Moreover, Beshir et al. (2022) used a double-hurdle model and 312 sampled households to examine the factors influencing the adoption of the tef-Acacia decurrens-charcoal production agroforestry system (TACPA). The study hypothesised that the factors influencing the decision to adopt the TACPA system may differ from those determining the intensity of adoption. The findings revealed a favourable relationship between TACPA system adoption and intensity of use; nevertheless, we discovered some differences in the factors impacting the two decisions. Credit, plot ownership, membership in farmers' associations, primary road distance, asset ownership, farmers' experience and labour availability, family size, livestock ownership, tenure security, and availability of marginal land are all important factors influencing TACPA system adoption. Furthermore, according to Fru et al. (2018), 20% of smallholder farmers in the Nkolbisson Forest of central Cameroon have only a few years of formal education. It was also observed that 55% of farmers thought the collection, storage, and transportation of feedstocks, as well as the pyrolysis itself, were costly.

Furthermore, farmers over the age of 40 were more willing to use biochar than younger farmers, owing to greater availability to resources such as land, labour, and capital. Likewise, Gitau et al. (2018) and Rogers (2020) found that local beliefs and constructions can influence smallholder farmers' adoption of biochar technology. Farmers opted to buy pre-packaged biochar rather than produce their own since biochar production is similar to charcoal production, which is a lower-class vocation. As a result, it was acknowledged that producing biochar risked lowering farmers' social status. Moreover, Peter et al. (2022) discovered that farmers aged 40-60 are more actively involved in biochar production and application than other age groups. Farmers aged 40 to 60 believed that their comparatively long agricultural experience, spanning from years with relatively higher yields to recent years with an experienced decrease in annual harvest, helped them understand the potential significance of biochar in retaining soil fertility and mitigating the negative effects of climate change. It was also discovered that farmers in this age group (40-60) owned critical resources such as cultivating land, manpower, and finances, all of which could be employed for biochar manufacture and application, in contrast to younger age groups. It was also discovered that farmers aged 40-60 have larger family responsibilities, necessitating the availability of revenue to meet their families' demands, compared to younger or older farmers. Furthermore, their research revealed that a greater level of education (years spent in school) among smallholder farmers was considered to have a beneficial influence on their decision to use biochar technology. It revealed that 76% of respondents had completed primary education, with 17% engaged in biochar production and application. Furthermore, it was shown that smallholder farmers could barely write and count after receiving primary school. This level of public education did not encourage their use of biochar technology. As a result, their understanding of biochar's biophysical and chemical properties was inadequate, necessitating the use of biochar-knowledgeable extension officers to explain and promote biochar system adoption. According to their study, 85% of respondents were men. 26% of all polled guys used biochar technology. Male farmers in Tanzania are often more fortunate than female farmers in terms of resource access and mobilisation opportunities, including land. These male privileges are mostly granted by the patriarchal system, which is widely upheld by customary law. The study demonstrates that women were not permitted to make land-related decisions in the absence of their husbands, although they frequently worked as labourers in agricultural activities. Furthermore, widows and single mothers were expected to seek counsel from male relatives before making agricultural decisions, owing to a strong patriarchal structure that undermined women's empowerment. Furthermore, Okyere and Kornher (2023) demonstrated that carbon farming training enabled farm households to apply organic fertiliser and improved their evaluations of soil quality, maize productivity, and return on maize production.

2.11. Understanding Impact Evaluation and Its Challenges

Measuring the effects of agricultural innovation is a difficult issue because of the challenge in the quantification of innovation effects; this characteristic is a major theme in contemporary development economics. Although there is an empirical evidence mountain indicating that the introduction of new technologies in farming can revolutionize the livelihood of farmers in rural areas, the task of establishing such a connection using observational evidence is notorious (Ndoro et al., 2014; Khonje et al., 2015). The very essence of this conflict is that the counterfactual issue: a researcher would be able to see the performance of an adopter at the moment, but they would never be able to see how the very person would have fared had he/she turned down on the technology (Asfaw et al., 2012). Agricultural adoption is a voluntary choice as opposed to a non-random choice because unlike a laboratory environment where a scientist would randomly assign a treatment to a control group to dissect variables, agricultural adoption is not random. The farmers will decide to be innovative according to their own calculations on the interior, which is a huge impediment to the statistical accuracy (Shiferaw et al., 2014).

In the past, most research has tried to avoid this complication by applying a simple Ordinary Least Squares (OLS) regression, which regards adoption as a yes or no variable. Nevertheless, this quick fix is quite frequently flawed and it is likely to give biased or inconsistent estimates. Three significant obstacles to the success of OLS in the specified context are expectedly identified as self-selection bias, endogeneity, and the so-called trap of missing data (Shiferaw et al., 2014).

Such a bias is due to self-selection since at the beginning adopters and those who are not adopters are typically quite different. A farmer who decides to employ a technology such as biochar may be more motivated or more educated or even risk-takers than his or her neighbor. Unless a researcher takes these inherent differences into consideration, the researcher risks giving credit to technology that is actually not successful due to his or her ability to drive and manage (Danso-Abbeam and Baiyegunhi, 2018). The issue of endogeneity is closely associated with this. Most of the characteristics affecting the decision of a farmer like personal values or working ethic cannot be observed by the researcher. Since these unobservable factors also affect the end yields and income, they cause a correlation between the error terms of the adoption decision and the result, which actually confuses the findings (Teklewood et al., 2013).

Moreover, according to Wooldridge (2003), investigators always have to fight a counterfactual void. Due to the fact that we can only see the result of the road taken we cannot see the road not taken, this makes it an inexplicable mystery. The problem of reverse causality the chicken and egg problem of development makes this complexity even more complicated. Although we suppose that adoption can raise the welfare, it is also as reasonable to believe that high initial welfare households have the financial buffer that they require to risk new technology in the first place.

These statistical challenges in the end drive the point that more sophisticated analytical tools are required. In order to go beyond the simple correlations and give a consistent estimation of the role of innovation in the lives of smallholders, scholars need to use measures that will be able to isolate the actual effect of adoption by the confounding variable of individual and environmental factors. It is vital to fill these gaps when determining the policies that indeed empower farmers and where the advancements in technology can make a real change to the actual and quantifiable increase in food security and family well-being.

2.12. Impact Evaluation Techniques in Agricultural Technology Adoption

To find the statistical clarity, researchers have put into use the broadest range of regression models to measure the actual impact that new technologies make on lives. Since Heckman treatment effects and Tobit models to more complicated double-hurdle and fixed effects models, it has always aimed to uncover the layers of the selection bias and endogeneity (Smale & Mason, 2014; Ehiakpor et al., 2016; Danso-Abbeam et al., 2018). However, there is one vexed problem about this: these tools are very good at finding correlations, but they do poorly at the what if- how to predict the same group of farmers correctly in a counterfactual situation.

A new generation of econometric strategies has become central in order to eliminate these challenges when working with cross-sectional data. The generalized propensity score, the conditional mixed process (CMP) and above all Propensity Score Matching (PSM) and Endogenous Switching Regression (ESR) have become the standard in the modern impact evaluation.

Propensity Score Matching (PSM) is also commonly used due to its intuitive reasoning and is essentially the creation of a statistical twin to each adopter by matching him or her with a non-adopter with nearly identical observable features. This enables making a much more reasonable comparison of results such as yield or income. PSM however has a blind spot which is it can only match what the researcher can see. It has a hard time explaining observable attributes of success that cannot be observed such as a farmer having an innate drive or grit that would also be considered.

Here is where Endogenous Switching Regression (ESR) model comes in its handy. The ESR framework is also complex enough, in contrast to PSM, to capture the visible data as well as the hidden, unobservable factors that tend to confuse the impact estimates. The consideration of the adoption as a switch changing a farmer to a new structural regime makes ESR a more comprehensive view of the actual benefits of innovation. Although all these methods also have their own advantages and disadvantages, they seem to be prevalent in the literature, indicating an underlying reality in research: the measurement of the effect of a new seed or a bag of biochar needs an analytical tool as subtle as the decision-making that the farmers make in general.

2.12.1. Heckman Selection and Treatment Effect Methodologies

In 1979, Heckman proposed one such sample selection model that has been a standard in research effort to de-tangle the knots of selection bias. The genius of the Heckman technique is that it consists of two phases. To start with, a Probit model is employed to approximate a selection equation, which is basically why this or that person appeared in a particular group. Based on this a statistical correction factor called the Inverse Mills Ratio (IMR) is obtained. The second step involves the entry of this IMR in an ordinary least squares (OLS) outcome equation as an extra explanatory variable. In so doing, the bias that would otherwise corrupt the results is soaked up by the model and a clearer estimation of the actual impact is obtained.

Although the Heckman model is logically elegant, and has an ability to remove the bias of selectivity, it is not an omnipresent remedy. It is well known to be sensitive to its underlying distributional assumptions, when the data is not strictly distributed normally the reliability of the model can soon become shaky. Moreover, although it is an effective instrument in some data types, it is severely limited in some cases where applied to a study involving dichotomous treatment variables the yes or no situations that are prevalent in technology adoption studies. To much contemporary researchers, although Heckman provided the foundation of the creation of a bias correction, such strict demands frequently justify the inclusion of a more lax set of econometric options.

2.12.2. Propensity Score Matching Technique

Propensity Score Matching (PSM) is a widely used tool for assessing the influence of agricultural intervention programs or innovations on a certain outcome variable. PSM is a nonparametric estimate method that eliminates the requirement to describe any functional form or distribution for random error terms. This technique is useful because it allows you to investigate the effects of a treatment on both the treated and control groups' future results (Heckman and Vytlacil, 2005). PSM is primarily about matching treated individuals with control counterparts based on their expected chance of receiving treatment, depending on observable covariates (Rosenbaum and Rubin, 1983; Wooldridge, 2003; Heckman and Vytlacil, 2005). There are two key assumptions underlying the use of PSM. First, the Conditional Independence Assumption (CIA) is the assumption under which the decision to receive a therapy is randomized, assuming that the covariates are known (Abadie and Imbens, 2006; Takahashi and Barrett, 2013). Second, the Common Support Assumption (CSA) requires major similarities in the features that are observed between the participants and non-participants of the program; those participants and non-participants should have an equal probability of being included in either category (Takahashi and Barrett, 2013). Assuming these, the method can be used to measure the Average Treatment Effects on the Treated (ATT) indicating the mean possible outcomes changes between the treated and non-treated groups in the zone of common support (Wossen et al. 2015). The PSM method is employed through a two-step estimation. It is initially assumed that the treatment or independent variable is a binary choice dependent variable whose regression, either Probit or Logit, is performed, and then propensity scores are made on each individual observation. Second, non-treated counterparts that have the same propensity score values are compared with treated individuals and the ATT is estimated (Abadie and Imbens, 2006). One disadvantage of PSM is however that it is incapable of taking into consideration the hidden biases because it can only correct observable heterogeneity to the degree it is reliably computed (Oduol et al., 2011).

2.12.3. The Endogenous Switching Regression Technique

The method of the Instrumental Variable (IV) approach and the Endogenous Switching Regression (ESR) in particular is a rather advanced set of tools, which can be used to decompose the numerous biases that tend to obscure agricultural studies. Regardless of the presence of blatant selection bias, latent endogeneity, or the missing data of the counterfactuals, these techniques allow isolating the true effect of a technology due to the noise of personal situations. The IV method is based on a definite functional form and a definite assumption regarding the nature of the distribution of error terms to operate (Abadie and Imbens, 2006).

The key element of the IV model is the necessity of an instrument, at least one variable that significantly alters a farmer toward adoption without any direct connection to the ultimate result, e.g. yield or income. In this general scheme, researchers mostly have two major directions the Local Average Treatment Effect (LATE) and the ESR method. LATE is valued due to its flexibility; it has extremely low structural requirements and an analysis of the impact of the treatment can be conducted credibly even in the absence of an official control group (Oduol et al., 2011).

Nonetheless, the ESR model is the stronger option in the case of most multifaceted agricultural research. Unlike the intercept shift, it establishes different equations of the treatment and control groups altogether. This is because adopters and non-adopters may respond differently to the same environmental or social factor. ESR helps us not to distort our estimates due to the endogeneity introduced by the self-selection, since more motivated or skilled farmers are the ones that decide to innovate (Shiferaw et al., 2014). Finally, the capability of ESR to represent interactions among the adoption status and the other variables enables the latter to be considered one of the most qualified methods of mapping the real impact of new technology on the livelihoods in rural areas.

2.12.4. Multinomial Endogenous Switching Regression Model

Based on the principles of binary selection models, Bourguignon et al. (2007) proposed Multinomial Endogenous Switching Regression (MESR) model, which has been developed to identify the complexity of multiple choices. However, in the real world, farmers seldom have to make such a simple yes or no choice but instead, they usually have to decide between a set of competing technologies or engage in a series of mutually exclusive interventions. The MESR model has become a significant instrument that helps the researcher to isolate the relative effects of these interacting decisions (Di Falco and Veronesi, 2013; Teklewold et al, 2013).

The MESR has an architectural power of its two stage, regression based approach. This structure is said to permit endogenous selection, that is, it is aware that the factors that prompt a farmer to use one particular type of technology instead of the other is in most cases, associated with the outcomes that the researcher is attempting to quantify. At the first level, Multinomial Logit (MNL) model is utilized to plot the various factors, which can be social, economic or environmental-based, which drives a household to a particular type of adoption.

After these adoption patterns, the second stage then applies Ordinary Least Squares (OLS) in the independent assessment of welfare determinants in each separate group. The MESR offers a granular perspective on the impact of various regimes of technology on a single outcome variable, e.g. household income or food security, by estimating the effect of each type of adopter and non-adopter separately on that outcome (Kassie et al., 2014; Mabe, 2018). Such capability of comparing three or more decisions at the same time guarantees that the model captures the reality, which is not only to be a simplified and binary form of reality but actually to be multifaceted. For example, when determining the influence of adopting two or more technologies (or even participating in two or more project interventions) on farm productivity, MESRM can be used (Kassie et al. 2014). A binary endpoint switching regression model gives the decision maker only two options: adopt, not adopt, or participate.

The basic assumption is that a company or farmer will use a combination of two or more technologies to maximize the overall discounted expected utility or benefit. MESRM assesses the impact of a set of activities on an outcome variable while adjusting for both observable and unobservable heterogeneity (Teklewold et al., 2013).

2.13. Review of Empirical Studies on Adoption of Sustainable Agricultural Practices and Its Impacts

The agricultural economics discourse has carefully traced the transformational strength of Climate-Smart Agriculture (CSA), how such agricultural innovations act as a life raft to rural families. On the one hand, researchers across the African continent have stopped making mere observations to demonstrate that indeed these technologies do not just grow crops, but they completely transform the health and wellbeing of smallholder communities. As an example, the utilization of climate-resistant groundnut varieties and organic fertilizers in Mali, Ghana, and Nigeria resulted in a hidden ripple effect that not only increased the yields but, as Tabe-Ojong et al. (2023) found, also improved the score of food consumption. This implies that to the underprivileged communities, CSA is no longer an option but a straight route out of food insecurity.

One such theme is that of the synergy of adoption. Statistics indicate that individual technologies are beneficial but they are the most effective when combined. Setsoafia et al. (2022) employed the Multinomial Endogenous Switching Regression (MESR) model to decouple the intricate net of relations between household demographics and extension services that promote the adoption of Sustainable Agricultural Practices (SAPs) among farmers in Ghana. Their results were startling: when farmers adopted a triple-threat strategy of combining better seeds, better forms of fertilizers, and better water conservation, they gained huge income and food security as compared to those who only used one or two. This effect of a higher-order suite is reflected in Nsabiman and Adom (2024) in Rwanda, where the authors discovered that the payoff of technology is most precise when the farmers have implemented systems of integrated technology as opposed to single tools.

This trend of group achievement can be observed in a variety of regional sceneries. Mutenje et al. (2016) in Malawi found that maximum yield spikes were achieved when the marriage of better storage conditions with high yielding maize varieties was involved. On the same note, Teklewold et al. (2013) discovered in Ethiopia that although combined adoption increased maize income, it also changed the domestic ecosystem within the farm, with such practices as conservation tillage decreasing the need of nitrogen fertilizer but unintentionally increasing the household labor and pesticide demands. These are subtle clues that make us remember that adoption of technology is a game of balancing between income, labor and environmental input. It also seems that the effect of such technologies is the most significant among those that need it the most. Habtewold (2021) noted that in Ethiopia, multidimensional poverty alleviation was more pronounced among the most impoverished household connected with higher consumption and non-food spending. In the meantime, Egeru et al. (2022) developed a sobering and but critical counterfactual in Uganda: farmers have continued to be low food security, but their status would have been much worse had they not incorporated CSA practices, such as disease and soil management.

The environment and institutional context, nevertheless, is the ultimate predator of success. As we saw in Zimbabwe by Mujeyi et al. (2021) distance to market is a physical barrier; resulting in a longer walk to input markets, the greater the distance the less the chances of adoption. On the other hand, the availability of climate data and livestock ownership are stimulants, as they give farmers the assurance and funds to become more innovative (Egeru et al., 2022). The data is universal: no matter which country we are talking about, be it wheat productivity in Ethiopia (Zegeye et al., 2022), or maize productivity in Kenya (Wekesa et al., 2018), the only way to ensure the resilience of the smallholder population is the coordinated, strategic use of climate-smart technologies, on the one hand, and an efficient information and market access infrastructure, on the other.

2.14. The impact of biochar adoption

Although the biochar discourse in the global community has been accelerating, the empirical data on its particular contribution to the welfare of households in the farm is yet to be developed.

Among the academics, there remains a debate on how these benefits are shared among various groups of agricultural activities and the social population. Sub-Saharan Africa is a region that has been especially affected by this knowledge gap in its research of soil carbon mitigation methods specifically the application of biochar and compost has been an exceptionally thin research area despite the susceptibility of the region to soil degradation.

Okyere and Kornher (2023) have recently filled this gap by assessing a five-year integration effort that was spearheaded by the University of Ghana. This was not a technical demonstration project, but a comprehensive training initiative aimed at educating the farmers in Northern Ghana to learn techniques of biochar and compost production using the waste materials that were available in their area. In order to make the impact comprehensive, the program incorporated home waste sorting, business skills, and biotechnology awareness in the curriculum. Nevertheless, just like any voluntary program, it is difficult to assess its effectiveness due to non-random adoption. Simple comparisons would yield biased outcomes and exaggerate the effectiveness of the technology in case the most motivated farmers are also the ones who attend the training.

To cut-off this statistical noise, the study employed rigorous econometric procedures such as doubly robust treatment effect estimates. Through these advanced robustness checks the study could explain the effect of selection bias and give a far better idea of the effect of biochar training on actually moving the needle regarding welfare in semi arid areas. Curiously enough, the program was not confined to one crop; it was aimed at a combination of various staples such as maize and rice and cash crops such as soya. The wide application is also a great addition to the literature, in that it implies that soil carbon reduction is not merely a specialized environmental policy but a universal device with a broad appeal to rural populations.

Lastly, the experiment illustrates that well-designed methods of carbon farming, especially training programs on soil climate mitigation measures can mitigate a limitation in adopting soil fertility practices and enhancing agricultural yields of farm households, which will enable them to afford food and other necessities and services, which in turn will lead to welfare, such as poverty reduction.

Okyere et al. (2024) predict that long-term carbon farming training will increase participation in farmer group activities, resulting in greater knowledge of resilience to climatic shocks, adoption of soil health practices, increased agricultural productivity, and, ultimately, resilience to food insecurity. They add to the literature on carbon farming in SSA by analysing freshly acquired data from three semi-arid locations in Northern Ghana. They look at a 5-year (2015–2020) project funded by the United States Agency for International Development (USAID). The project trained chosen farmer groups in three regions of Northern Ghana on how to make biochar and compost using locally available agricultural byproducts. Field trials with farmers and agricultural extension agents were conducted at the project sites.

As a result, the project took a transdisciplinary approach, involving farmers in the design and execution of field and plot trials as well as the application of biochar and compost to farmer fields throughout the 2019 and 2020 agricultural seasons. They discover that carbon farming instruction has a large and statistically significant impact on crucial aspects of resilience, such as access to basic services, assets, and social safety nets. They also discovered a modest increase in adaptive capacity. In terms of food security, they discover a statistically significant effect on the food consumption score (FCS) and household dietary diversity score (HDDS). However, they did not find statistical significance for other food security indicators such as the household and child food insecurity experience scales (FIES and CFIES), which could be attributed in part to the 12-month timeframe (rather than the past 24 hours, 7 days, or 30 days) used in previous studies to estimate the indicators. They determined that a long-term training project on biochar and compost production in three Northern Ghana regions improved not just crucial food and nutrition security indices but also fundamental components of development resilience. Previous research, such as Ouédraogo et al. (2001); Badu et al. (2019); Frimpong et al. (2021); and MacCarthy et al. (2020), investigated the potential of biochar to boost agricultural productivity.

2.15. Conceptual framework

The Sustainable Livelihood Framework serves as the conceptual foundation for the investigation. According to the Sustainable Livelihood Framework, households have varying levels of resource endowment and capabilities, as well as varying degrees of exposure to the institutions and policies that shape the environment in which they operate, and the interaction of these factors determines their livelihood choices and, as a result, welfare outcomes. SLF provides five major types of resources from which households can assess their production potential, particularly in light of the shocks, trends, and seasonality of their livelihoods, as well as the institutional structures and processes that they encounter.

These resource categories include natural resources such as soil, water, biodiversity, and associated environmental services; social capital, which comprises social networks, claims, and affiliations; Human capital relates to human resources, skills, and knowledge base. Physical capital refers to infrastructure and industrial equipment. Cash, credit, debt, savings, and other economic assets are all forms of financial capital. Depending on the level of endowment in these resource categories, households devise and identify potential livelihood strategies that would result in optimal welfare outcomes such as increased income and well-being, decreased vulnerability to economic shocks and natural disasters, improved food security, and continued use of available natural resources. According to Asfaw et al. (2018), farm households' willingness to embrace climate-smart technologies may be influenced by livelihood assets. They influence household preferences and decisions, labor availability, and liquidity restrictions (Dercon, 1996; Feder et al., 1985; Rosenzweig and Binswanger, 1993). Thus, they evaluate the vulnerability of rural smallholder families to climate change and related calamities, as well as productivity gains and household well-being (Gatzweiler and Von Braun, 2016;

Asfaw et al., 2018). Livelihood assets interact with institutions, influencing households' adaptive capacity and well-being.

Formal and informal institutions have a substantial impact on household innovation adoption and livelihoods. Their influence could be either facilitating or inhibitive. They would boost innovation by increasing access to markets, manpower, and credit. They can also shape family preferences by instilling ideas and values, which in turn impact manufacturing, marketing, and consumption decisions. Another key element influencing farmers' decisions to accept innovations is farmer heterogeneity in terms of the benefits and costs of the innovations (Tesfaye, 2019).Adoption of biochar is thought to have an impact on welfare outcomes, or the end results of farm households' livelihood strategies, such as food security (dietary diversity, daily calorie consumption, food consumption expenditure), human capital development (child growth), income (farm revenue or profits), poverty, risk coping (informal insurance, involuntary diet change), and natural resource sustainability (Wright et al., 2012). This framework proposes that various types of livelihood assets (physical, financial, social, human, and natural capital) and institutional factors, both formal and informal (access to agricultural institutions services, favourable policies and laws, culture, etc.), serve as the foundation for households' choices of livelihood strategies, including the adoption and use of biochar, which in turn influence their welfare outcomes, particularly welfare outcomes. Figure 3.13 summarises the mechanism by which biochar adoption is expected to affect welfare outcomes, specifically farm income, household wellbeing, and increased agricultural commercialisation.

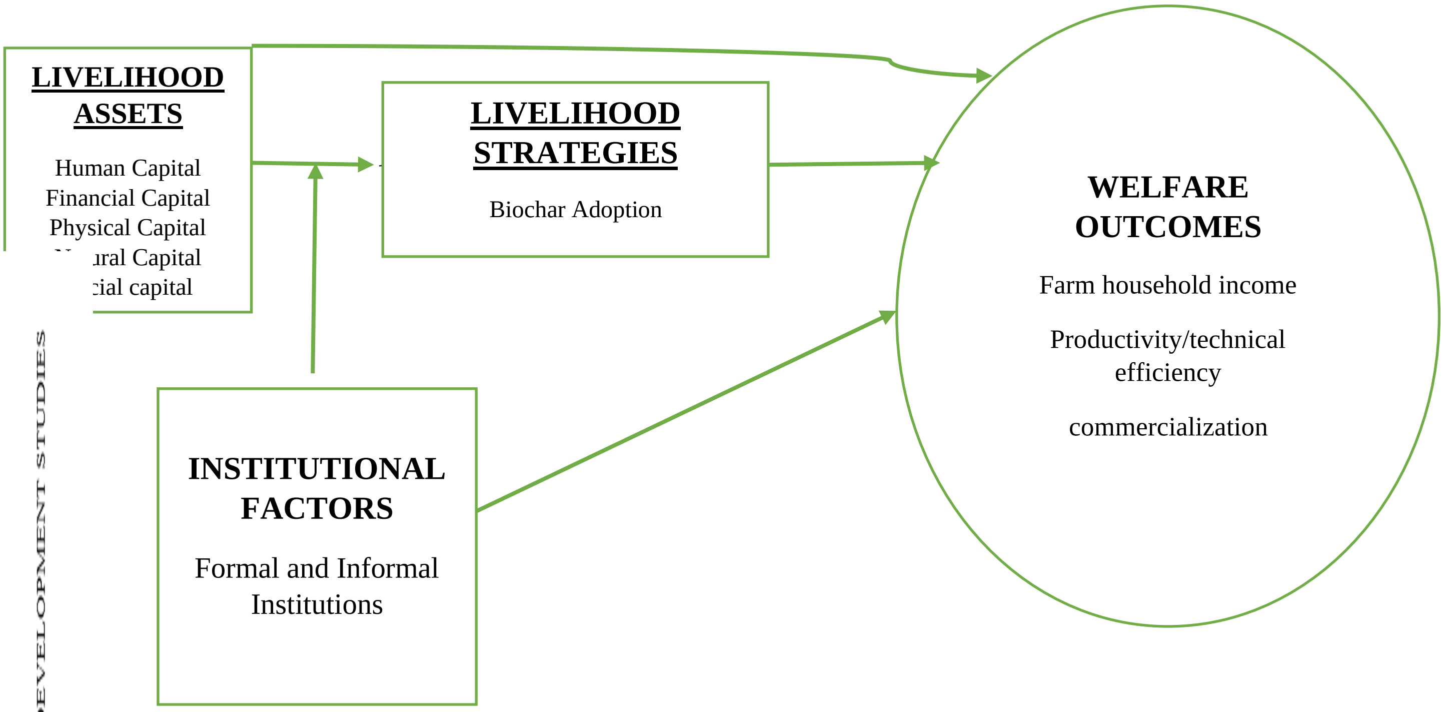


Figure 3.13: The linkage and impact pathway of the adoption of biochar and household welfare

2.15. Gaps in the literature

While numerous studies have documented biochar’s effects on soil properties and crop yields. Most of these studies have focused largely on agronomic effects such as soil fertility, crop yield, and organic carbon content (Kiobia *et al.*, 2019; Bi *et al.*, 2022; Joseph *et al.*, 2021; Islam *et al.*, 2021; Cen *et al.*, 2021; Blanco-Canqui, 2021; Al-Omran *et al.*, 2021; Gebisa & Regasa, 2024) while neglecting the socio-economic dimensions of adoption. There remains limited empirical understanding of how biochar influences production efficiency, market participation, and household welfare among smallholder farmers. The absence of coordinated national biochar programmes, weak institutional support, and limited market linkages for biochar products have further constrained its diffusion and potential impact (Kumar *et al.*, 2025; John *et al.*, 2025; Pahari, 2025)

CHAPTER THREE

METHODOLOGY

3.1. Introduction

This chapter presents the methods and approaches adopted in this study including the study area, study design, philosophy, sampling method, data collection procedures, data analysis and ethical considerations

3.2. Study Area Description

The investigation was conducted in Ghana's Upper West Region, one of the country's sixteen administrative regions. The territory was founded in April 1983 as a result of the previous Upper Region's split and has since had a significant social-economic and cultural impact on Ghana's northern region (Upper West Regional Co-ordination Council [UWRCC], 2025). The region is divided administratively into eleven districts: Wa Municipal, Wa West, Wa East, Jirapa, Lambussie, Nandom, Nadowli-Kaleo, Daffiama-Bussie-Issa, Sissala East, and Sissala West. Wa, the region's capital, serves as both an administrative center and a hub for commerce, trade, and administration (UWRCC, 2025).

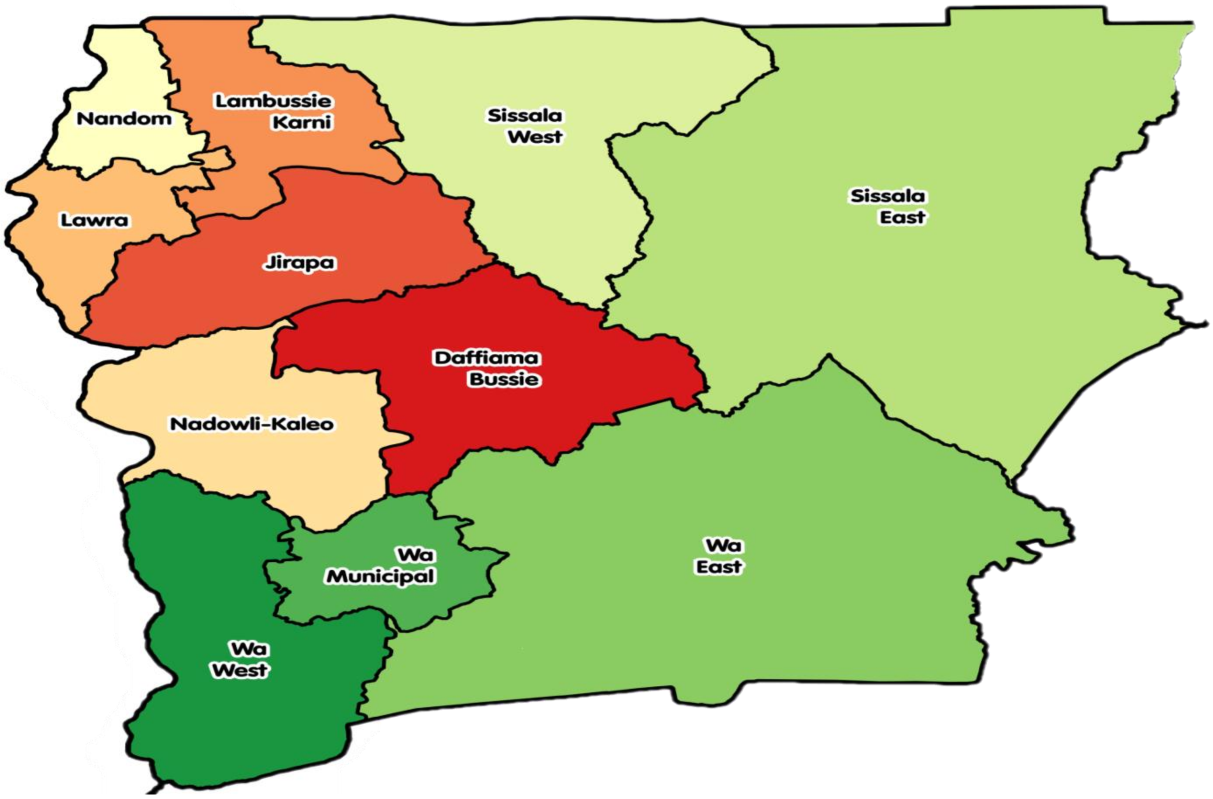
Geographically the Upper West Region is in the north-western part of Ghana with the latitudes falling between 9 0 30 N and 110 N and the longitudes between 1 25 W and 2045 E. It has international frontiers with Burkina Faso to the north and west whilst internally, it is surrounded by the Upper East and North East Regions to the east and Savannah Region to the south. The area has a size of about 18,476 square kilometers which is an equivalent of 12.7 percent of the total area of Ghana. The fact that it is close to other countries in the ECOWAS such as Burkina Faso, Mali, Niger and Cote d' Ivoire makes it easier to trade with them and especially in agricultural products like groundnuts, shea nuts, and mangoes (UWRCC, 2025).

The 2021 Population and Housing Census population figures show that the Upper West Region has a population of 904,695 people that includes 441,799 males (48.8%) and 462,896 females (51.2). The demographic composition is quite young, with about 53 percent of the population being below the age of 20, which implies that the country has a large number of prospective workers to engage in agricultural production (UWRCC, 2025). However, the region has a large dependency ratio which is estimated at more than 91 percent which puts a lot of pressure on economically productive people leading to never ending poverty and vulnerability of livelihood. Its climate is typified by the unimodal type of rain, which has one rainy season, which falls between May and September and is around 1,150mm per annum. This is succeeded by a prolonged dry season which is due to the harmattan winds. The temperature ranges between 21 C to 32 C in average every month, although the weather can go to 40 C before the rains and drop to an average of 20 C at the harmattan (UWRCC, 2025). Such climatic conditions have a heavy impact on agricultural activities especially the dominance of rain-fed crops including groundnuts, maize, millet and sorghum.

Topographically, the region of the Upper West is mostly composed of topographies that are gently rolling in nature, with an altitude of approximately 200 meters in the Black Volta Basin, and about 350 meters in the Wa-Burkina Faso ridge. Black Volta and Kul]=ylvania rivers form the major drainage systems and they offer a chance of development of irrigation. Geographically, the region is located in two major savannas, the Guinea Savanna of the south and the Sudan Savanna of the north. These areas provide different kinds of vegetation cover, some of which have economic value like shea, dawadawa, mahogany, baobab and Acacia (UWRCC, 2025).

Agriculture also forms the major part of the regional economy, with over 80 percent of the population being involved in smallholder farming. Agricultural practices have been mostly rain-based, small-scale and on limited land of an average of 2.5 acres (UWRCC, 2025). Production of groundnut is very essential especially as one of the cash crops which sustain the household incomes and also help in food security. Nevertheless, agricultural productivity is limited due to unreliable rainfalls, insufficient irrigation infrastructure, and market inaccessibility, despite the adoption of the government programmes, including the Planting for Food and Jobs and Rearing for Food and Jobs programmes (UWRCC, 2025).

The ownership of land in the area is communal to a great extent and the ownership of customary rights lies in the authorities of the family and heritage. Though land is not an issue of concern in general, the size of holdings is a limiting factor to large-scale farming activities. Moreover, the poverty level is high and endangers the long-term sustainability of rural livelihoods in the area due to bushfires, overgrazing, and deforestation (UWRCC, 2025).



Source: Local Government Services [LGS]. (2025)
Figure 4.1: Map of Upper West Region

3.3. Research Design

This study adopted a research design that was quantitative based on a cross-sectional survey to understand the effect of biochar adoption on the productivity, technical efficiency, market engagement, and welfare outcomes of smallholder farmers in the Upper West Region of Ghana (Ghanad, 2023; Kinyua, 2023).

The design adopted also enabled the comparison of results between farmers that had and had not adopted the biochar technology hence offering empirical evidence on the effect of using biochar on the performance of smallholder farms. Primary data was collected using a structured interviewer based questionnaire that recorded information relating to household socio-demographic factors, farm and production factors, biochar adoptions, marketing, and welfare factors. Given that the standardized questionnaire was used, this made the responses consistent across the respondents and minimized the possibility of interviewer bias. In order to further enhance data quality, we used trained local enumerators who were conversant with the local languages and also, they were conversant with the community settings to administer the survey. The questionnaire was pretested before the actual data collection exercise on communities that had similar socioeconomic status as those of the study area. This pilot test served to determine ambiguous, misleading or culturally inappropriate items and the instrument was revised to be more understandable and context relevant and to facilitate its compatibility with the objectives of the study. A refined questionnaire was then administered to gather information on sampled households in the sampled districts.

The cross-sectional data that was generated was used in econometric analysis to determine the impact of biochar use on productivity, efficiency, commercialization, and household welfare. Although the application of cross-sectional data does not allow drawing definite causal conclusions, it is still a reliable picture of current situations and relationships. It is anticipated that the results of the research will provide useful evidence in informing the agricultural and environmental policy choices and act as a benchmark to future longitudinal or panel studies of sustainable agricultural technologies and rural welfare improvement in Ghana.

3.4. Research Philosophy

The research is based on the positivist research philosophy that focuses on the use of observed, objective, and measurable evidence to describe any relation between variables (Ali, 2024; Maretha, 2023). Positivism is an approach that believes that social phenomena may be systematically observed and measured as well as analyzed in some way similar to the natural sciences, thus allowing the production of findings that are replicable and generalizable. This philosophical stand is very apt to the current study that aims at studying the impact of biochar use on the productivity of farm among groundnut farmers in the Upper West Region of Ghana by using quantitative methods and statistics.

The positivist approach to knowledge considers that it exists without reference to personal beliefs and perceptions, and the researcher should take an unbiased and value-free position in the research process. As a result, data gathering and research is done in an organized and methodological form, and the end conclusions are made based on empirical evidence that can be verified, not based on the subjective judgements. In line with this approach, the study utilizes primary data obtained through structured questionnaires to empirically test hypotheses and examine the relationship between biochar adoption welfare, commercialization and productivity outcomes.

The adoption of positivism also supplements the deductive method of analysis of the study in which there are already known theories and other previous empirical studies on the adoption of agricultural technology, its productivity, and welfare that influence the formulation of testable hypothesis. These hypotheses are then tested on, based on quantitative data, where inputs use in relation to the output and adoption rate of the new technology are taken as key variables and assessed through standardized measures to increase reliability and validity.

Through a positivist penumbra, the study appreciates the fact that the behavioral and the technology adoption choice of the farmers can be mathematically analyzed and elucidated with reference to statistical models. The evidence that shall be created in this fashion is anticipated to be utilized in informed policy formulation and based on creation of special interventions that shall be oriented at the scaling of sustainable agricultural technologies and boosting the livelihood of smallholder farmers in Ghana.

3.5. Sampling Procedure

To select the respondents to take part in the research, a multi-stage sampling process was used. The method was deemed suitable because it enabled a wide representation of the groundnut farmers in diverse agro-ecological and socioeconomic conditions in the Upper West Region of Ghana as well as practical feasibility and methodological appropriateness.

The MEDA-GROW 2 project trained groundnut and soyabean farmers on biochar production and utilization in the Upper West, Savannah and Northern regions. At the time of the study only farmers in Upper West had used the Biochar in groundnut production for the 2024/2025 season with the remaining two regions at training stage. Thus, the Upper West region was purposively selected to able to get farmers who have adopted and used biochar for groundnut production. This decision was also inspired by the fact that the region is the lead producer of groundnut in Ghana (MOFA, 2021) and the crop is a significant cash crop in the area and also a staple crop because it is the crop mostly planted by the smallholder farmers as a source of revenue and as a source of household food security and as a source of livelihood. Moreover, the agro-climatic conditions and predominant farming systems in the region provide it with a good setting in which groundnut production dynamics can be studied in northern Ghana (MOFA, 2021).In the second phase, 7 districts were identified with support from the monitoring and evaluation department of MEDA based on the prevalence of biochar adoption and groundnut production. Out of the 7 districts 4 were randomly selected for the study. On the whole, the chosen districts provide heterogeneity in terms of production conditions, institutional support, and access to markets, thus enabling the study to have spatial and contextual differences to influence groundnut farming.

At the third stage, with support from MEDA M&E Officers, communities were clustered into biochar adopted and non-biochar adopted communities in each of the selected districts and out of each cluster, 4 communities were randomly selected given 8 communities per district and a total of 32 communities.

Final stage, a proportionate sampling was used to selected 168 farmers Jirapa (64 adopters and 104 non-adopters), 196 farmers (64 adopters and 132 non-adopters) from Lawra, 168 farmers (64 adopters and 104 non-adopters) from Wa West and 32 farmers (10 adopters and 22 non-adopters) given a total of 564 farmers as illustrated in Table 4.1

Table 4.1: Distribution of Groundnut Farmers by District and Community

	Jirapa	Lawra	Sissala	Wa West	Total
Biochar	64	64	10	64	**202**
Non-biochar	104	132	22	104	362
Total	168	196	32	168	564

Source: Field Survey (2025)

Based on the Yamane's formula: $n = \frac{N}{1+N(e^2)}$ (Yamane, 1967) we at the time of the

$n = \frac{N}{1+N(e^2)}$ = 20,000/1+20,000(0.05) = 392.16. ≈ 392.

Thus, the minimum sample for the study was 392 respondents. However, 564 farmers were interviewed

3.6. Data Collection Procedure

This research assumed a quantitative data collection method where the researcher gets information based on groundnut production households. Primary data were believed to be the most appropriate data source since it is acquired directly through the respondent thus making it more credible and objective by invalidating any chances of earlier modification or interpretation. The data collection was well designed and incorporated consistency, accuracy, and validity in assessing the effects of biochar adoption on the farm productivity of groundnut farmers in Northern Ghana.

The primary data were obtained with the help of a structured questionnaire that was created with the aims of the study. The tool has recorded the detailed data on household demographic and socioeconomic characteristics, adoption of biochar at farm level, resource accessibility, input use and management, productivity indicators, institutional support accessibility, market participation, income, and welfare indicators at the household level. Questions were mostly close ended to ensure a similar response and an easy analysis in terms of quantitative and statistical responses.

To test the questionnaire, a pilot was carried out in a groundnut growing community whose features matched those of the study area but not included in the study sample. The pilot exercise allowed clarifying, poorly constructed or culturally unsuitable items and made corrections to enhance the feasibility, order, and validity of the instrument. Upon these refinements, the questionnaire was finalized and was allowed to be used in the field.

The data were collected by means of Computer-Assisted Personal Interviewing (CAPI) on the Kobo Collect application on Android-based tablets and smartphones. This online system of data collection enhanced the level of accuracy in data collection since there was a reduction in the mistakes in entering data manually and this also enabled them to align and validate the responses in real time. The filled questionnaires were submitted on a daily basis on a central server, which was safe and was monitored. The principal investigator conducted regular investigation on the quality of the data with the aim of identifying missing responses, inconsistencies, and outliers and giving immediate feedback to the field team to ensure high data quality standards are observed.

The primary interviewees were the heads of the households as they were the central actors in making decisions on farm management, inputs to use, and technology adoption. In case household heads were not available, an adult member of the household who had sufficient knowledge of the production activities in the farm was interviewed. *In order to have good communication and understanding, the interviews were carried out in English and Dagaare*.

The data collection exercise involved a collection of data that would refer to the 2024-2025 agricultural production cycles hence a total picture of the biochar use and the resultant productivity. The ethical principles were applied rigorously during the process which involves giving clear information to the respondents, taking out informed consent, making sure the participation is voluntary and the confidentiality of all the data obtained.

3.7. Pre-Test and Reliability of Data Collection Tool

Prior to the actual survey of the main field, the piloting of the structured questionnaire was conducted to determine its clarity, reliability and appropriateness in reaching the research goals. The pilot test was carried out on twenty (20) groundnut farmers who were randomly chosen among four districts in the Upper West Region from the lists obtained from MEDA using Rand formula in excel made offive respondents from each in districts. This exercise was done to ensure that the questions were well worded, culturally acceptable and could produce relevant and accurate information. It also gave a chance to assess the clarity of instructions, the order of questions and the feasibility of the whole process of data collection.

Analysis of data collected during the pilot survey was done using the Statistical Package of the Social Sciences (SPSS) version 25. To determine the internal consistency of the questionnaire items, Cronbach alpha coefficient was used (Cronbach, 1951). The reliability coefficient of 0.85 that followed is a high internal consistency level among the items contained in the instrument. As per the recommended Cronbach alpha coefficients of DeVellis (2012), George and Mallery (2003), and Kline (2000), a Cronbach alpha value of between 0.80 and 0.90 indicates good reliability and the correctness of the instrument in the quantitative empirical analysis.

In addition to the reliability testing, the content validity was also enhanced by expert review and the response given by the agricultural extension officers and the academic supervisors and a sample group of groundnut farmers. Their suggestions were used towards clarification of unclear items, bettering of the wording of technical questions, and also made the instrument more accurate. Changes based on the pilot results were made to make sure that the questionnaire questions sufficiently reflected the most important constructs pertaining to biochar adoption, farm productivity, commercialization, and household welfare outcomes.

After these revisions, the questionnaire was considered to be reliable, valid, and context specific to collection of quantitative data of groundnut farmers in the study area.

3.8. Ethical Considerations

The aspect of ethics was given a lot of priority during the research process. Prior to the fieldwork, the Ethics Review Committee of the University of Development Studies (UDS) gave the ethical approval. Moreover, the appropriate district agricultural offices and traditional authorities in the study area obtained official permission letters to provide the institutional consent and acceptance of the research by the community.

All the respondents were given a clear and detailed information about the study before their participation. The researchers outlined the purpose of the study, the type of data that was going to be gathered, how long each interview will last, and how the information would be utilized. The study participants were told that their participation in the study was absolutely voluntary and they could withdraw at any point without being required to explain what they are doing or they were not expected to face any undesirable repercussion.

Each of the respondents was informed of the process of consent prior to the beginning of the interview process. In order to ensure privacy of the participants, no personal identifiers such as names, residential address, or contact details were taken. Any data supplied by the respondents was not disclosed to anyone, and was used in academic and research applications.

The hard-copy questionnaires and the digital records were stored safely by the password-protected systems and only by the principal investigator and authorized members of the research team. In processing and analysing data, identities of respondents were anonymized to offer further protection of respondent identity. These ethical protection measures guaranteed that the rights and dignity of participants were respected and that accountability and responsibility in the study were upheld.

3.9. Theoretical Framework

The theory backing this study is the random utility theory.. The fundamental assumption that is made in this study is that groundnut farmers are rational economic agents who make decisions whether to use biochar and the level of using it based on the expected benefits to the costs involved. The net gains are instead used to make adoption decisions and not random or habitual behavior.

The model also assumes a risk-neutral farm household whose decision-making is to maximize the utility which is modeled as a function of net returns at the farm level (π). These choices are made in the wider perspective of the technology of production available, the current prices of inputs and outputs, and the market limitation. In this context, the adoption of biochar will have an impact on productivity and profitability thus, improving the yields of farms and consequently on the welfare of households. This production technology is supposed to be quasi-concave in the variable input (k), and determined by environmental and household specific variables (x). The problem of optimization by the farmer can be stated as:

$$Max_k U(\pi) = Max_k U[PQ(K, X) - w'K] \qquad (1)$$

In this formulation, U represents the utility function, P is a vector of output prices, Q is the production function dependent on the quantities of inputs (K) and environmental or household characteristics (X), while w is a vector of input prices.

Let $K_B \subseteq K$ denote the component of inputs associated with biochar application. The adoption of biochar is expected to improve soil quality, enhance crop productivity, increase net returns, and ultimately raise household welfare. Therefore, a farmer's decision to adopt biochar depends on the comparison between the expected utility from adoption $U_a^*(\pi)$ and expected utility from non-adoption $U_n^*(\pi)$. Adoption takes place when the expected utility from adopting biochar is greater than that from not adopting it, that is:

$$U_a^*(\pi) > U_n^*(\pi) \qquad (2)$$

Although these utilities are not directly observable, the adoption decision can be expressed in terms of a latent variable that reflects the unobserved difference in utilities between adopters and non-adopters. The observed adoption decision is therefore defined as:

$$U(\pi) = \begin{cases} 1, if\ U_a^*(\pi) > U_n^*(\pi) \\ 0, if\ U_a^*(\pi) \leq U_n^*(\pi) \end{cases} \qquad (3)$$

The latent utility associated with the adoption decision depends on observable household and farm characteristics as well as the intensity of biochar-related inputs, and can be expressed as:

$$U(\pi_i) = \delta' K_{iB} + \alpha' X_i + \tau_i \qquad (4)$$

where α and δ are vectors of parameters to be estimated, i represents the household, and τ_i is a random error term assumed to have a zero mean and constant variance σ_τ^2. Because biochar adoption is expected to have a positive effect on farm returns, a rational groundnut farmer will continue to increase the level of adoption until the expected marginal return from adopting biochar equals the expected marginal return from non-adoption, expressed as:

$$\frac{\partial E(\pi_\alpha)}{\partial K_{iB}} = \frac{\partial E(\pi_n)}{\partial K_{iB}} \qquad (5)$$

In practice, however, several constraints may prevent farmers from reaching the optimal adoption level. Factors such as labour shortages, financial limitations, imperfect information on soil and climate management, and weak institutional support may all limit the extent to which biochar is adopted (Rogers et al., 2021; Jansen, 2023). As a result, the real adoption intensity will not be as high as could have been. In addition, access to credit, level of education, contact with extensions, security of land tenure, and training on using biochar are some of the variables that are important in determining the adoption decision and intensity of adoption. The combination of these factors has an effect on whether a household turns out to be a non-adopter, a partial adopter or a full adopter and consequently on the contribution of the adoption to better productivity, commercialization and welfare results.

3.10. Methods of Data Analysis

The research adopted a quantitative analytical approach in order to respond to the research objectives. The data gathered was coded, cleaned, and analyzed in STATA version 18. The descriptive statistics (means, frequencies, and standard deviations) were employed to provide the summary of the socioeconomic features of respondents and to describe the overall characteristics of systems of groundnut farming in the Upper West Region of Ghana. These preliminary statistics provided important context and formed the basis for interpreting patterns and relationships examined in the subsequent econometric analyses. To assess the effect of biochar adoption on groundnut commercialization, the recursive bivariate probit was used. The study also analysed the second objective: effect of biochar adoption on farm household welfare using the endogenous switching regression model. Finally, the third objective: effect of biochar adoption on groundnut output and technical efficiency was acheived using Sample Selection Stochastic Production Frontier Model (Greene Approach).

3.11. Empirical Estimation Methods

3.11.1. Stochastic Production Frontier Model (Greene Approach)

To examine the impact of biochar adoption on production efficiency among groundnut farmers, the study adopted the SFP as proposed by Greene in 2010 (Greene 2010).

The general form of the stochastic production frontier for each farmer (i) at time period t is defined as:

$$Y_{ij} = f(X, d_i)\exp\left(V_{ij} - U_{ij}\right) \qquad (6)$$

where Y_{ij} denotes the output of the i-th farmer; X is a vector of input quantities (land, labour, seed, fertilizer and agrochemicals) and other explanatory variables; d_i is a binary variable capturing the effect of participation; V_{it} is a two-sided error term which is independently and identically distributed N $(0, \sigma^2)$ random error; and the U_{it} is a non-negative random variable, associated with technical inefficiency in production. The subscript j refers to $d_i = 1$ for beneficiary (treated) and $d_i = 0$ for non-beneficiary (control). Farmers self-select in participating in an intervention and as a result of this selection bias may arise due to unobserved and observed characteristics. These biases need to be addressed when estimating the SPF model in order to get unbiased and consistent estimates of output and technical efficiency. A model introduced by Greene (2010) was used to deal with biases from unobserved characteristics within a SPF formulation. According to Greene (2010), Heckman's (1979) sample selection model is unsuitable for nonlinear model as in the case of SPF so Greene (2010) introduced the sample selection SPF model to account for biases in unobserved characteristics (e.g managerial skills). This model assumes that the unobserved characteristics in the selection equation are correlated with the noise in the stochastic frontier model; hence, Greene's contribution can be seen as a significant improvement of Heckman's self-selection specification for the linear regression model. The sample selection and SPF models, along with their error structures, can be expressed as:

Sample selection: $d_i = 1[\alpha^I z_i + w_i > 0], w_i \sim N[0,1]$ $\qquad (7a)$

SPF: $\qquad y_i = \beta^I x_i + \varepsilon_i \sim N[0, \sigma_\varepsilon^2]$ $\qquad (7b)$

$$(y_i, x_i) \mathit{observed\ only\ when}\ d_i = 1$$

Error structure: $\varepsilon_i = v_i - u_i$

$$U_i = |\sigma_u U_i| = \sigma_u |U_i|,\ \mathit{where}\ \ U_i \sim N[0,1] \qquad (8)$$

$$v_i = \sigma_v V_i,\ \mathit{where}\ \ V_i \sim N[0,1] \qquad (10)$$

$$(w_i, v_i) \sim N_2[(0,1), (1, \rho\sigma_v, \sigma_v^2) \qquad (11)$$

Where d is a binary variable that is one for beneficiaries and zero for non-beneficiaries (control), y is output, z is a vector of covariates used in the sample selection equation, and x is a vector of inputs in the production frontier. The Greek characters α and β represent parameters to be estimated, while the characters in the error structure are typical of a stochastic frontier model. The parameter ρ indicates the existence or absence of selectivity bias.

The log likelihood for the model in (3.1.4) is formed by integrating out the unobserved |*Ui* | and then maximizing with respect to the unknown parameters. Thus,

$$\text{Log}\, L\,(\beta, \sigma_u, \sigma_v, \alpha, \rho) = \sum_{I=1}^{N} log \int_0^{\infty} f\,(y_i|x_i, z_i, d_i, |U_i|)\rho(|U_i|)d|U_i| \qquad (12)$$

The integral in this equation is unknown and must be approximated. Greene (2010) employs a two-step estimating strategy to streamline the process. The MLE of α in Probit equation (4) is consistent but inefficient. To estimate the SPF parameters, it is not necessary to re-estimate α. The estimates of α are taken as given in the simulated log likelihood. The Murphy and Topel (2002) correction adjusts the standard errors in a manner similar to Heckman's correction of the canonical selection model. Greene (2010) argues that non-selected observations (i.e., when,-*i*. = 0) do not provide information on the parameters to the simulated log likelihood. Therefore, the function to be maximized becomes:

$$\log L_{s,c}\,(\beta, \sigma_u, \sigma_v, \rho)$$

$$= \sum log \frac{1}{R} \sum_{r=1}^{R} \left[\frac{\exp\,(-\frac{1}{2}(y_i - \beta^I x_i + \frac{\sigma_u |U_{ir}|)^2}{\sigma_v^2})}{\emptyset(\frac{\rho(y_i - \beta^I x_i + \frac{\sigma_u |U_{ir}|)^2}{\sigma_\varepsilon + a_i})}{\sqrt{1-\rho^2}})} X \right] \qquad (13)$$

Where $a_i = \hat{\alpha} z_i$

The model's parameters are estimated using a traditional gradient-based methodology, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method, and the asymptotic standard errors are calculated using the Berndt-Hall-Hall-Hausman (BHHH) estimator. When ρ equals zero, the maximand converges to the basic frontier model's maximum simulated likelihood estimate. This gives us a way to compare the specification of the selectivity model to the simpler model using a (simulated) likelihood ratio (LR) test.

The estimating method aims to determine the sample's inefficiency (,-i) or efficiency (exp(−,u-i). Aggregate summary measurements, including the sample mean and variance, are frequently presented. Researchers also compute individual specific estimates of the conditional means based on the (Jondrow et al., 1982) (JLMS) result given by

$$E[U_i|\varepsilon_i] = \frac{\emptyset\lambda}{1+\lambda^2}\left[\mu_i + \frac{\emptyset(\mu_i)}{\emptyset(\mu_i)}\right], \mu_i = \frac{\lambda\varepsilon_i}{\sigma}, \varepsilon_i = y_i - \beta^I x_i \qquad (14)$$

In the usual method, this function is calculated using maximum likelihood estimations. In principle, we might repeat this calculation using the greatest simulated likelihood estimates. The alternate approach adopted here takes advantage of the simulation of the values of, u-i during estimate. According to Greene (2010), the technique yields a surprisingly identical answer to the JLMS plug-in solution demonstrated in the section.

3.11.2. Recursive Bivariate Probit Model (RBPM)

The decisions of smallholder groundnut farmers to adopt biochar and to engage in agricultural commercialization are intrinsically interrelated, each represented as a binary outcome. The Recursive Bivariate Probit Model (RBPM) is particularly suitable for analyzing such situations, as it allows for the joint estimation of two binary decisions that may be correlated. The model is described as “recursive” because it posits that the adoption decision precedes and potentially influences the commercialization decision, while reverse causality from commercialization to adoption is explicitly ruled out. This recursive formulation enables the RBPM to address endogeneity stemming from unobserved factors that could simultaneously affect both outcomes, such as managerial skills, risk preferences, or intrinsic motivation

Formally, the RBPM can be specified as follows:

$$y_i^* = x_i'\beta + \alpha_2 D_i + \varepsilon_1, y_i = 1[y_i^* > 0] \qquad (15)$$

$$D_i^* = z_i'\delta + \ \varepsilon_2, D_i = 1[D_i^* > 0], \binom{\varepsilon_1}{\varepsilon_2} \sim N\binom{0}{0}, \begin{pmatrix}1 & \rho \\ \rho & 1\end{pmatrix} \qquad (16)$$

Where:

D_i^* represents the latent propensity of farmer i to adopt biochar;

y_i^* represents the latent propensity of farmer i to commercialize agricultural produce;

D_i and y_i are the observed binary outcomes, taking the value 1 if adoption or commercialization occurs, and 0 otherwise;

x_i and z_i are vectors of explanatory variables affecting adoption and commercialization, respectively;

ε_1 and ε_2 are error terms jointly distributed as bivariate normal with zero mean, unit variance, and correlation coefficient ρ .

A statistically significant correlation coefficient $\rho \neq 0$indicates that unobserved factors jointly affect both adoption and commercialization decisions, validating the necessity of a joint estimation framework. By estimating the equations simultaneously, the RBPM ensures that the estimated effect of biochar adoption on commercialization is unbiased, consistent, and efficient. This framework provides a rigorous basis for analyzing the recursive and interdependent relationship between biochar adoption and commercialization decisions, making it particularly appropriate for evaluating technology adoption impacts in smallholder farming systems.

3.11.3. Endogenous Switching Regression Model (ESRM)

The ESRM was used to assess the effect of biochar adoption on farm household welfare measured by per capita income and expenditure. ESRM is able to correct possible endogeneity and selectivity bias which may emanate from other interventions for farmers (Fitawek &

Hendriks, 2021). Assuming we consider a latent continuous variable I* that is distributed normally with mean μ and variance σ^2. The ESR model can be given by

$I^* = \alpha Z_i + u_i$ (17)

$I_i = 1 \text{ if } I^* > 0$

$I = 0 \text{ if } I^* \leq 0$ ………………………………………………………………… (18)

Modelling the effect of Biochar adoption on the welfare of farmers under the ESRM gives two stages: The first stage is farmers decision to adopt in the sustainable practice (equation 1), and this is computed using the probit model. In the second stage, an Ordinary Least Square regression with selectivity correction is used to find the connection between the outcome variable and a set of explanatory variables relative to the participation decision. The use of the two regimes helps to overcome endogeneity and selection bias using the ESRM. The two outcome equations contingent on the adoption decision can be expressed as

$Y_{1i} = \beta_1 X_{1i} + \varepsilon_{1i} if\ I = 1$ (Adopters) $(19a)$

$Y_{2i} = \beta_2 X_{2i} + \varepsilon_{2i} if\ I = 0$ (Non-Adopters) (19b)

Where Y_{1i} and Y_{2i} are the outcome variables representing the welfare level of the farmer i for adopters and non-adopters respectively, X_{1i} and X_{2i} are the exogenous variables that are seen to affect adoption, such as farmer age, education, access to credit, and farm size, β_1 and β_2 are the coefficients of the parameters to be estimated and ε_{1i} and ε_{2i} are the error terms. In order to cater for endogeneity, the study introduce two instrumental variables i.e training on biochar production and awareness of biochar. The intuition is that farmers who received training on biochar production would be more inclined to adopt biochar because they have the capacity to produce and use it and would have good understanding of the benefits of biochar to the soil and by extension the crop. Also, regarding awareness of biochar, a farmer who is aware of biochar and its soil amendment and productivity enhancing qualities would be motivated to adopt biochar compared to a farmer who do not know no knowledge about biochar. However, whether a farmer receives training on biochar production, is aware of biochar or not has no direct effect on farmers welfare. It will only affect welfare through biochar adoption that will enhance productivity which will translate to better income and food security. It is assumed that the error terms have a tri-variate normal distribution with a mean vector of zero and covariance matrix as shown below

$$Cov(\varepsilon_{1i}, \varepsilon_{2i}, \mu_i) = \begin{pmatrix} \sigma^2_{\varepsilon 1} & \sigma_{\varepsilon 1 \varepsilon 2} & \sigma_{\varepsilon 1 \mu} \\ \sigma_{\varepsilon 1 \varepsilon 2} & \sigma^2_{\varepsilon 2} & \sigma_{\varepsilon 2 \mu} \\ \sigma_{\varepsilon 1 \mu} & \sigma_{\varepsilon 2 \mu} & \sigma^2_{\mu} \end{pmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(20)}$$

where $\sigma^2_{\varepsilon 1}$ and $\sigma^2_{\varepsilon 2}$ are the disturbance terms in the regime function in equation (2), σ^2_{μ} represents the disturbance term in the selection equation (1), $\sigma_{\varepsilon 2 \mu}$ is the covariance of the error term in equation (2) while $\sigma_{\varepsilon 1 \mu}$ is the covariance between ε_{1i} and μ_i, $\sigma_{\varepsilon 2 \mu}$ is the covariance between ε_{2i} and μ_i. It can be assumed that $\sigma^2_{\mu} = 1$ since it is estimable only up to a scalar (Madalla, 1983).

Therefore, the expected values from the regime functions are given as

$$E(\varepsilon_A | I = 1) = E(\varepsilon_{1i} | I = 1) = \sigma_{\varepsilon 1 \mu} \frac{\phi(\alpha Z_i)}{\Phi(\alpha Z_i)} \equiv \sigma_{\varepsilon 1 \mu} \lambda_{1i} \text{ where } \lambda_{1i} = \frac{\phi(\alpha Z_i)}{\Phi(\alpha Z_i)} \ldots\ldots\ldots\ldots \text{(21)}$$

$$E(\varepsilon_A | I = 0) = E(\varepsilon_{2i} | I = 0) = \sigma_{\varepsilon 1 \mu} \frac{\phi(\alpha Z_i)}{1 - \Phi(\alpha Z_i)} \equiv \sigma_{\varepsilon 2 \mu} \lambda_{2i} \text{ where } \lambda_{2i} = \frac{\phi(\alpha Z_i)}{1 - \Phi(\alpha Z_i)} \ldots\ldots \text{(22)}$$

where ϕ is the probability density function, and Φ cumulative density function. If the estimated $\sigma_{\varepsilon 1 \mu}$ and $\sigma_{\varepsilon 2 \mu}$ are significant, the absence of self-selection is rejected which implies that the decision to adopt and the outcome variable are interrelated (Maddala & Nelson, 1975).

Where λ_1 and λ_2 are the correlation coefficients between selection equation error term u_i and the error terms of the outcome equations ε_1 *and* ε_2. Treatment effects were also estimated. The average treatment effect on the treated and untreated (ATT and ATU) are calculated using the findings for the predicted values of the selection variable biochar adoption and non-adoption in actual and counterfactual.

$$E(Y_{1i}|I_i = 1, X_{1i}) = \beta_1 X_{1i} + \sigma_{\varepsilon 1 \mu \rho_1} \frac{\phi(\alpha Z)}{\Phi(\alpha Z)} \qquad (23)$$

$$E(Y_{2i}|I_i = 0, X_{2i}) = \beta_1 X_{2i} - \sigma_{\varepsilon 2 \mu \rho_1} \frac{\phi(\alpha Z)}{1 - \Phi(\alpha Z)} \qquad (24)$$

$$E(Y_{2i}|I_i = 1, X_{1i}) = \beta_2 X_{1i} + \sigma_{\varepsilon 2 \mu \rho_2} \frac{\phi(\alpha Z)}{\Phi(\alpha Z)} \qquad (25)$$

$$E(Y_{1i}|I_i = 0, X_{2i}) = \beta_2 X_{2i} - \sigma_{\varepsilon 1 \mu \rho_2} \frac{\phi(\alpha Z)}{1 - \Phi(\alpha Z)} \qquad (26)$$

The difference between the predicted values of the result variables from equations 23 and 25 is denoted by ATT. It is the difference between the anticipated value of the dependent variable for irrigation energy source adoption and the expected value if they did not adopt. ATU is the difference between equations 24 and 26, which estimates the difference in the expected value of the outcome variable for no adoption and if they had adopted an biochar.

3.12 Description of variables

Table 4.2: Description of variables

Variables	*Description*	Measurement		Apriori expectations	
Continuous			Biochar	commercialization	Welfare
Farmer age	Age of the farmer in years	Years	+	+	+
Household size	Number of people who eat from the same pot	Number	+	+	+
farmers experience	Years in groundnut production	Years	+	+	+
District capital distance	Distance in km to the district capital	Km	+	+	+
H income	Monthly income earing by the farm household	GHS			
H expenditure	Monthly expenditure of the farm household	GHS			
Groundnut size	Number of hectares in groundnut production	Ha		+	+
Seeds qty	Quantity of groundut seed used by the farmer in the production season	Kg	+	+	+
Pesticides qty	Quantity of pesticides used by the farmer in the production season	Kg	+	+	+
Distance to input dealers	Distance in km to the nearest input dealer	Km	+	+	+
Distance to plot	Distance in km to the farmers plot	Km	+	+	+
Categorical			+	+	+
Edu	Whether the farmer had formal education or not	1 Yes 2 No	+	+	+
Market access	Whether the farmer has access to market for farm produce	1 Yes 2 No	+	+	+
NGO Support	Whether the farmer benefits from an NGO	1 Yes 2 No	+	+	+
Remittances	Whether the farmer receive remittance	1 Yes 2 No	+	+	+
Agric extension	Whether the farmer received extension services	1 Yes 2 No	+	+	+
Input Credit	Whether the farmer accessed credit for farming	1 Yes 2 No	+	+	+
FBO	Whether the farmer is a member of a farmer based orgnaization	1 Yes 2 No	+	+	+
Married	Whether the farmer is married	1 Yes 2 No	+	+	+
JIRAPA	Whether the farmer is from Jirapa	1 Yes 2 No	+	+	+
Lawra	Whether the farmer is from Lawra	1 Yes 2 No	+	+	+
Sissala West	Whether the farmer is from Sissala West	1 Yes 2 No	+	+	+
Wa West	Whether the farmer is from Wa	1 Yes 2 No	+	+	+

	West				
Biochar Training	Whether the farmer received training on biochar production	1 Yes 2 No	+	+	+
Aware biochar	Whether the farmer is aware of biochar	1 Yes 2 No	+	+	+
Commercialization	Whether the farmer has commercialized his/her farm produce	1 Yes 2 No	+		+
Biochar	Whether the farmer adopt biochar	1 Yes 2 No		+	+

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the results and discussions based on the objectives of the study.

4.2. Summary statistics

The findings, as shown in Table 4.1, provide a comparative study of important socioeconomic and farm-level characteristics between farmers who utilized (adopters) and did not use biochar on their groundnut fields. Farmers in the pooled sample have an average age of 45.87 years, with an average of 45.53 years for biochar users and 46.07 years for non-biochar users. This shows that the bulk of farmers are in their economically active years and have extensive farming expertise. The age difference between biochar users and non-users was significant at the 1% level, demonstrating the importance of age in biochar uptake. Equally, farmers who use biochar were found to live farther from district capitals, with an average distance of 22.6 km compared to 20.2 km for non-users, and this difference is statistically significant at the 5% level. This may be attributed to the fact that biochar production takes place in rural areas due to availability of biomass compared to urban centers where district capitals are located. Also, the average household expenditure and income for biochar users are GHS 751.94 and GHS 1475.49 respectively per month, compared to GHS 470.90 and GHS 800.60 for non-users with the difference being statistically significant at the 1% level. These findings suggest that biochar adoption may be associated with improved household economic well-being, either as a result of increased productivity or as a reflection of more resource-endowed farmers being early adopters of new technologies. Biochar adopters were found to have higher farm sized compared to non-adopters and the difference was significant at 1%. This implies a positive association between biochar adoption and farm size. Also, the average liters of pesticides used was 5.94 for biochar adopters and 0.64 for non-adopters implying intensive use of pesticides among biochar adopters. Biochar adopters have on average 22.6km and 13.8km distance to district capital and the nearest input dealer respectively. Again, the distance from home to farm was 9.1km for biochar adopters and 2.9km for non-adopters. This suggests that farmers who adopt biochar farm far from their homes.

Table 4.1: Summary statistics

Variables	*Pooled*	*Biochar*	*No biochar*	*diff*	*t value*
Continuous					
Farmer age	45.872(11.241)	45.525(0.668)	46.066(0.637)	-0.541(0.988)	-0.55***
Household size	7.349(2.715)	7.317(0.191)	7.367(0.143)	-0.051(0.239)	-0.2
farmers exp	15.821(10.259)	14.95(0.700)	16.306(0.547)	-1.356(0.9)	-1.5
District capital distance	21.059(13.994)	22.628(1.286)	20.183(0.569)	2.446(1.226)	2**
H income	1042.315(45.337)	1475.49(91.49)	800.599(44.07)	674..89(90.26)	7.5***
H expenditure	571.554(23.95)	751.94(46.11)	470.896(25.59)	281.04(48.57)	5.79***
Groundnut size	2.555(1.724)	2.963(0.144)	2.328(0.077)	0.635(0.149)	4.25***
Seeds qty	24.932(28.735)	24.909(2.003)	24.945(1.520)	-0.036(2.526)	-0.00
Pesticides qty	2.541(15.103)	5.941(1.707)	0.643(0.223)	5.297(1.308)	4.05***
Distance to input dealers	11.778(13.617)	13.809(1.283)	10.645(0.526)	3.165(1.19)	2.65***
Distance to plot	5.146(12.719)	9.1(1.300)	2.939(0.367)	6.16(1.088)	5.65***
Categorical	*Pooled*	*Biochar*	*No biochar*	*diff*	*t value*
Edu	0.257(0.437)	0.148(0.025)	0.318(0.025)	-0.169(0.038)	-4.5***
Market access	0.851(0.356)	0.961(0.014)	0.790(0.021)	0.171(0.03)	5.6***
NGO Support	0.390(0.488)	0.629(0.034)	0.257(0.023)	0.372(0.04)	9.3***
Remittances	0.186(0.390)	0.242(0.030)	0.155(0.019)	0.088(0.034)	2.6***
Agric extension	0.424(0.495)	0.683(0.033)	0.279(0.024)	0.404(0.04)	10.1***
Input Credit	0.431(0.496)	0.624(0.034)	0.323(0.025)	0.3(0.042)	7.2***
FBO	0.676(0.469)	0.817(0.027)	0.597(0.026)	0.22(0.04)	5.5***
Married	0.784(0.412)	0.792(0.029)	0.779(0.022)	0.013(0.036)	0.35
JIRAPA	0.298(0.458)	0.406(0.035)	0.238(0.022)	0.169(0.04)	4.25***
Lawra	0.348(0.477)	0.129(0.024)	0.470(0.026)	-0.341(0.04)	-8.65***
Sissala West	0.057(0.232)	0.079(0.019)	0.044(0.011)	0.035(0.021)	1.7*

Wa West	0.298(0.458)	0.386(0.034)	0.248(0.023)	0.138(0.04)	3.45***
Biochar Training	0.558(0.497)	0.901(0.021)	0.367(0.025)	0.533(0.037)	14.25***
Aware biochar	0.754(0.431)	1(0.000)	0.616(0.026)	0.384(0.035)	11.2***
Commercialization	0.739(0.439)	0.847(0.025)	0.679(0.025)	0.167(0.038)	4.4***

The results also indicated that biochar adopters are more likely to have access to extension services compared to non-adopters and this was significant at 1%. This implies that farmers who have access to extension access are more likely to adopt biochar compared to their counterparts. Moreso, over 62% farmers who received credit adopted biochar and about 63% of farmers who received NGO support adopted biochar.

Along with that, Farmer-Based Organization (FBO) membership is higher among biochar users (82%) than the non-users (60%). These results indicate that institutional support and the involvement of organization of farmers can have supported biochar adoption. In addition, about 15% of biochar adopters are educated compared to 32% of non-adopters who are educated. This implies that educated farmers are less likely to adopt biochar compared to non-educated farmers and this was significant at 1%. The finding is plausible because farmers who adopted biochar during the study were also producers, thus educated farmers who are likely to be employed in other non-farm work and most likely would not have time to produce their own biochar.

Moreover, biochar users are much more market integrated (96% vs. 79%), meaning that adopters have a superior market access. This is in line with the higher commercialization rates where 85% of biochar users and non-users are at 68% respectively which indicates that the availability of markets not only stimulates the adoption of technology but also enables the farmers to enjoy higher returns due to the adoption of better production practices. Spatially, the distribution of biochar adoption varies across districts. A higher proportion of biochar users are located in Jirapa (40.6%) and Wa West (38.6%), while non-users dominate in Lawra (47%). This spatial pattern is consistent with the locations of project interventions. Importantly, Training and awareness about biochar show the most pronounced differences. Almost all biochar users (90%) received training on biochar use, while only 37% of non-users did. Similarly, awareness levels are universal among users (100%) but only 62% among non-users. These results strongly indicate that information dissemination and practical training are the most decisive factors influencing biochar adoption. They also validate the effectiveness of extension and NGO-led sensitization efforts in enhancing farmer participation in soil improvement technologies.

4.3. Determinants of biochar adoption among groundnut farmers

The probit results as illustrated in *Table 4.2*, is the determinants of adoption of biochar among groundnut farmers in the Upper West Region. The results showed a Likelihood Ratio (LR) chi2(22) = 301.75 with a probability (Prob > chi2 = 0.0000), Pseudo R2 = 0.5131, and a Log likelihood = -143.19234 implying the explanatory variables fits the model. *Table 4.2* presents both coefficients and marginal effects, but discussions are based on the marginal effects because coefficients only explain the direction of effect of the explanatory variables on biochar adoption but not magnitude of the effect. Out of the 20 variables used in the analysis, 9 variables including farm size, household size, seed quantity, market access, input credit, per capita expenditure, district of residence (Jirapa, Lawra, and Sissala West), and training on biochar were significant in determining biochar adoption.

Groundnut farm size was found to be positively related to biochar adoption and this was significant at the 1% level. This means that 1 hectare increase groundnut farm size will lead to 1% increase in the probability of a farmer adopting biocharholding all else constant. The finding is in line with priori expectations because larger farms provide both financial flexibility and risk absorption capacity, enabling farmers to experiment with new technologies without jeopardizing household wellbeing. In addition, farmers managing larger farms may experience greater soil nutrient depletion, increasing the incentive to adopt fertility-enhancing practices like biochar. This was consistent with the findings of Chao et al. (2024), who found that as the farmer's farmland increased, so did the likelihood of adopting sustainable agriculture practices. The findings are also consistent with those of Wongnaa et al. (2024), who discovered that farmers who own large tracts of land are more likely to adopt new technologies. However, the findings contradicted those of Zakaria et al. (2020), who indicated a detrimental influence of farm size on the adoption of agricultural technologies.

Also, household size shows negative relationship with biochar adoption, suggesting bigger households are less likely to adopt biochar compared to smaller households. This implies that an increase in household size 1 person will lead to a 1% decrease in the probability of a farmer adopting biochar holding all other factors constant. The finding is inconsistent with expectations because biochar production and application are labour intensive, thus, bigger household are likely to have readily available labour to meet both production and application needs compared to smaller households. However, the result is plausible because larger households are often characterized by high dependency ratios, which constrain disposable income and labor allocation and by extension technology adoption.

Again, seed quantity revealed a positive and highly significant association with biochar adoption. By implication, an increase in the quantity of seed used by 1kg will lead to a 0.1% increase in the probability of a farmer adopting biochar holding all other factors constant. Farmers who use larger seed quantities are likely cultivating more land or pursuing higher yields, suggesting they are commercially driven and thus more motivated to adopt complementary yield-enhancing inputs like biochar.

More so, market access was negative and significant at 5% level to biochar adoption, meaning farmers who have access to market are less likely to adopt biochar compared to those who do not have access. This is in conformity with expectation because farmers who have access to market have readily access to inorganic fertilizers and commercial inputs at low transaction and transportation costs compared to those who do not. Consequently, distant farmers turn to rely on locally available, low-cost substitutes like biochar, which they can produce from crop residues.

Table 4.2: Determinants of biochar adoption among groundnut farmers (probit model)

Variable	*Coefficient*	*Marginal effect*
Education	0.016(0.111)	0.003(0.021)
farm size	0.052**(0.022)	0.010***(0.003)
Farmer age	-0.007(0.010)	-0.001(0.002)
Household size	-0.054***(0.012)	-0.010***(0.003)
District capital distance	0.026(0.024)	0.005(0.005)
Seeds qty	0.003*** (0.001)	0.001***(0.000)
Pesticides qty	0.002(0.001)	0.000(0.000)
Markt access	-0.326**(0.131)	-0.061**(0.031)
NGO Support	0.360(0.247)	0.068(0.054)
Remittances	0.046(0.061)	0.009(0.010)
Agric extension	0.291(0.191)	0.055(0.030)
Credit access	0.262*** (0.057)	0.049***(0.016)
Distance input dealers	0.008(0.019)	0.002(0.003)
Distance plot	0.009(0.011)	0.002(0.002)
FBO	0.073(0.225)	0.014(0.044)
Married	-0.208(0.316)	-0.039(0.064)
Jirapa	1.453***(0.297)	0.273***(0.026)
Lawra	-1.933***(0.406)	-0.363***(0.037)
Sissala West	-1.268***(0.427)	-0.238**(0.106)
Training on biochar	2.365***(0.039)	0.444***(0.041)
_cons	-2.681***(0.635)	

Furthermore, access to credit was a positive function of biochar adoption, implying farmers who have access to credit are 4.9% more likely to adopt biochar compared to their counterparts without credit access. The finding is consistent with expectations because access credit relaxes farmers' liquidity constraints, enabling them to purchase production inputs, acquire labour for biochar production and application and therefore would be more likely to adopt biochar. The findings confirm that of Miine et al. (2023) and Ngango et al. (2023) who found farmers who accessed credit to be more inclined to adopting digital agricultural solution and agroforestry technology respectively because they became financially endowed and thus could afford multiple solutions compared to their counterparts who did not have access to credit.

The district dummies indicate strong spatial effects. Farmers in Jirapa were found to be more likely to adopt biochar compared to those in Wa West (Based district). However, the results revealed that farmers in Lawra and Sissala West were less likely to adopt biochar compared to farmers in Wa West holding all else constant. The intuition here is that local institutional presence, project interventions, and exposure levels differ across districts. Jirapa may have benefited from the targeted training initiative of GROW 2 Project under MEDA that promote biochar production and utilization, while the other districts may have had limited outreach.

Finally, training was positively and significantly related to biochar adoption at 1% level of significance. This implies that farmers who receive training on biochar production and utilization are more likely to adopt biochar compared to their counterparts who did not receive training. This finding is logical because farmers who receive biochar training are likely to have good understanding of the production processes and the benefits of using biochar.

4.4. Determinants of commercialization and the effect of biochar adoption

The purpose of this section was to investigate the influence of biochar adoption on farmer groundnut commercialization using a recursive bivariate probit model. Table 4.2a shows the results. The table also includes estimates for other factors that are significantly associated with commercialization and biochar uptake. The *Wald Chi*^{2} test of independence found that the biochar adoption and commercialization equations are dependent, as evidenced by the statistical significance of the *Wald Chi2* test of independence (Wald Chi2 (45) = 268.72 and a p-value of 0.000) at the 1% level of significance. The rho which tests for correlation between the error terms of the biochar adoption and commercialization equations was also significant implying; 1) unobserved factors jointly affect both adoption of biochar and commercialization, 2) the presence of endogeneity, and 3) the recursive bivariate probit model is appropriate for estimating the results. In attempt to address the endogeneity, the study used training on biochar and awareness of biochar as instruments. The choice of these instruments is based on the premise that farmers who are aware or received training on biochar production woulld enhances knowledge and technical capacity regarding biochar production and application, thereby increasing the likelihood of adoption. However, training on biochar production or awareness of biochar is not expected to directly influence farmers' commercialization behaviour, such as their decision to sell agricultural produce or the degree of market participation, except through its effect on biochar adoption. Instead, any potential influence of training or awareness on commercialization occurs indirectly through improved soil fertility and productivity resulting from the adoption of biochar.

The validity test showed significant relation between the instrument and biochar adoption and insignificant to commercialization implying relevance and exogeneity of the instrument.

The results show that adopting biochar has a clear and statistically significant positive effect on commercialization at the 1 per cent level. In practical terms, this means that farmers who use biochar are more likely to sell their produce in output markets than those who do not. This outcome is consistent with a wide range of previous studies, which have consistently found that the adoption of improved agricultural technologies encourages greater market participation among smallholder farmers (Akter et al., 2021; Awotide et al., 2016; Singbo et al., 2021; Tabe-Ojong, Mausch, et al., 2022; Tabe-Ojong, Smale, et al., 2022). Conceptually, the technologies like biochar enhance the productivity and stability of farms by enhancing the quality of soils and yield, as well as alleviating the risk of production. Consequently, smallholders would be in a better position to create marketable surpluses and engage more reliably and steadfastly in output markets (Key et al., 2000; Renkow et al., 2004). This interpretation is further evidenced by Ethiopia. Tabe-Ojong Jr and Geffersa (2024) use panel data to discover that there is a positive correlation between fertiliser use and commercialization of smallholders. Collectively, these results indicate that the adoption of productivity enhancing technologies can be a significant stepping stone that can see smallholders leave subsistence farming, expand their interactions in the market, and eventually benefit incomes and help enhance the overall rural economy.

Farm size was found to have positive and significant relationship with farmers commercialisation. This means that groundnut farmers with bigger farms are more likely to commercialised than their counterparts with smaller farms. The finding is in line with expectations because bigger farms are associated with larger farm output and by extension remarkable surpluses after meeting household food consumption requirement. Again, farmers with larger land size are likely to enjoy economics of scale, translating to lower cost of production and making them competitive in commercialisation. This is also related to the study done by (Nguyen Do Anh Tuan, 2006; Mayo et al., 2025) which emphasized that land accumulation is a critical factor that promotes land productivity and agricultural commercialisation.

Moreso, household size was found to be positively and significantly related to groundnut farmers commercialisation holding all else constant. This suggests that an increase in household size will increase commercialization among groundnut farmers in the study area. The finding is plausible because larger households typically provide labour for farm operations, thus, enabling farmers to intensify production and thereby increasing commercialization.

Similarly, farm experience was positive and significant to commercialization. This implies that an increase in a farmer’s experience will translate to an increase in commercialization holding all factors constant. The finding is understandable because experience farmers are likely to be endowed with good farm management skills and a better appreciation of groundnut price changes and buyers’ requirements. Again, farmers with experience are also likely to adopt yield enhancing technologies and manage risk associated with commercialization. The result is in line with Endalew et al. (2020) who reported farm experience as a positive function of wheat commercialization. The result is also consistent with previous studies (Mazengia, 2016, Kabiti et al., 2016, Haji et al., 2018)

Furthermore, access to market was associated with higher likelihood of commercialization. This suggest that farmers who have access to market are more likely to commercialize than their counterparts who do not have access to market. This finding is plausible because readily access to market provides farmers with information on the price and demand conditions and incentivized farmers to produce in commercial quantities. This is contrary to the finding of Endalew et al. (2020) who reported market distance to be negatively and significantly related to commercialization. The findings of Hailua et al. (2015), Mazengia (2016), and Tufa et al. (2014) noted that market access had a negative and significant effect on commercialization, inconsistent with this study.

Access to agricultural extension service showed a positive and significant relationship with commercialization. This means that farmers that got extension service have higher chances of commercializing than farmers who did not. This highlights the importance of dissemination of information in boosting commercialization. The extension agents provided farmers with not only good agronomic practices to increase yield, but also market information and skills in post-harvest management that preserve the quality of groundnut. Extension officers also, link farmers to input and output market, thus, facilitating commercialization. This finding is line with that of Endalew et al. (2020) who indicated that extension access had a positive relationship with wheat commercialization.

Table 4.2a: Effect of biochar adoption on commercialization using recursive bivariate probit

	Commercialization	Biochar
Edu	0.0361(0.0864)	0.0431(0.254)
farm size	0.171***(0.0452)	0.0476(0.0547)
Farmer age	-0.000735(0.00104)	-0.00520(0.00582)
Household size	0.052***(0.009)	-0.049**(0.022)
Farmers exp	0.007***(0.001)	0.025**(0.011)
District capital dist	-0.007(0.005)	0.024***(0.008)
Seeds qty	-0.00390***(0.0012)	0.003***(0.000)
Pesticides qty	0.002***(0.000)	0.002***(0.000)
Markt access	0.432***(0.021)	-0.373***(0.077)
NGO Support	-0.121(0.082)	0.339(0.286)
Remittances	-0.018(0.182)	0.064(0.072)
Agric extension	0.095***(0.032)	0.262***(0.074)
Input Credit	0.060**(0.025)	0.229***(0.059)
Dist input dealers	-0.008***(0.002)	0.0090(0.011)
Dist plot	0.022***(0.003)	0.011***(0.000)
FBO	0.057**(0.027)	0.062(0.055)
Married	0.061**(0.027)	-0.213***(0.000)
JIRAPA	0.275***(0.018)	1.432***(0.011)
Lawra	-0.831***(0.054)	-1.929***(0.049)
Sissala West	-0.016(0.084)	-1.237**(0.498)
Training on biochar		2.329***(0.023)
Aware of biochar		6.378***(0.283)
Biochar	*0.189****(0.001)	
Constant	-0.974***(0.274)	-9.734***(0.570)
Log likelihood	*-404.07215*	
Wald chi2(45)	*268.72*	
Prob > chi2	*0.0000*	

**** p<0.01, ** p<0.05, * p<0.1 Wald test of rho=0: chi2(1) = 411.026 Prob > chi2 = 0.0000*

Credit access was found to be a positive function of groundnut commercialization, implying that financial constraints are critical inhibiters to commercial production. This is in line with priori expectations because accessing credit enable farmers to meet their input (fertilizer, improved seed, chemicals etc.) obligations to boost production and by extensions surpluses to be put on the market. Abu and Issahaku (2017) reported that farmer with access to finance sell higher quantities of their farm produce than financially excluded farmers. Other literature (Abu and Issahaku, 2017; Manda et al., 2021; Sekyi et al., 2020) have shown how access to credit stimulate agricultural commercialization.

Similarly, member of FBO was significant and positive to commercialization. This implies that farmers who are members of FBOs are more likely to commercialize their groundnut production compared to their counterparts who are not. This is explainable because FBOs facilitate members access to extension services, market information, farm inputs and also allow members to enjoy collective bargaining power, thus, reduce transaction cost. Farmers are also likely to received training on production and marketing through participation in FBO activities which could translate to higher yields and marketable surpluses. The result corroborates with the finding of Abu et al. (2024) and several studies in the literature (Abu and Issahaku, 2017; Aku et al., 2018; Hao et al., 2018, Kyaw et al., 2018). Aku et al. (2018) noted that farmer organization improve farmer welfare by improving market access, reducing transaction cost to agricultural marketing, and providing social capital.

On the contrary, distance to input dealers was a negative function of groundnut commercialization and this was significant 1% level of significance. This suggests that an increase in distance to the nearest input dealer will reduce the probability of a groundnut farmer commercializing. This is understandable because increase in distance to input dealers adds to input costs, thus, limiting farmers access to inputs in the form of fertilizer, improved seeds and chemical which are crucial to enhancing productivity. A respondent said "*my child I don't have access to improved seeds and pesticides though I want to use them, sometimes I will even have the money to buy but how to get is the problem. You can buy seeds and by the time you receive it, the fare cost is equal to the seed cost.*"

Additionally, distance to farm plot was significant and positive to commercialization, suggesting that the farther the farm plot from home, the higher the probability of commercialization. This is in conformity to expectations because farms located near homes are usually smaller and mostly unavailable for large scale production. However, bigger size farms are mostly farther from homes and support commercial production. One of the respondents had this to say "*if you want to farm seriously to meet your family consumption and also sell to make money, you have to go far. The plots around are smaller and less productivity*" the second respondent also has this to say "*we only farm some few crops we need as a household nearby but our main farms are farm from the community. When we harvest we sell some and bring some home for our own consumption*".

Finally, locational heterogeneity showed mixed and significant effect on groundnut commercialization. The analysis revealed that farmers Jirapa were more likely to commercialized, while those in Lawra were less likely to do so compared to farmers in Wa West. The disparity in commercialization can be attributed to variation in soil fertility, institutional support and project intervention (GROW 2) across the districts.

4.5. Treatment effects of biochar adoption on commercialization

By estimating the average treatment effect (ATE), Average treatment effect on the treated (ATET), and average treatment effect on the untreated (ATUT), we are able to ascertain/estimate the impact of biochar adoption on commercialization.

From the analysis, the ATE of 0.05 at ($p<0.01$), implies that biochar adoption would increase commercialization by 5% on average if biochar is randomly adopted across the entire sample. Also, ATET of 0.025 at ($p<0.01$) suggests that farmers who adopted biochar showed 2.5% increase in commercialization. The result is plausible because farmers who adopt biochar for soil amendment are more likely to achieve higher yield and by extension marketable surpluses due to the improvement in soil fertility.

Table 4.2b: Effect of biochar adoption on groundnut commercialization

	dy/dx	*std. err*
ATET	0.025***	0.001
ATE	0.050**	0.001
ATU	0.250	0.730

In contrast, the ATUT was estimated at 0.250, but insignificant suggesting uncertainty in the effect of biochar on commercialization among non-adopters. This result is encouraging given the fact that respondents in this study are women smallholder farmers who produce groundnut on small land holdings. Thus, sustainable intensification of modern inputs is a good alternative to enhance food production and smallholder women's participation in output market. The results aligned with the finding of Tabe-Ojong and Geffersa (2024) who found fertilizer adoption to be associated with 13% increase in market participation and an associated 25% increase in the quantity of maize sold in the markets. The study attributed the increase in market participation to the yield effect associated with fertilizers use (Tabe-Ojong et al. 2023; Tesfay, 2020).

4.6. Effect of biochar adoption on welfare

4.6.1. Correlates of biochar adoption and household per capita income

Columns 2 and 3 of Table 4.3a presents the effect of biochar adoption on farm household income in the Upper West region. The Endogenous Switching Regression (ESR) model was used to examine both the factors influencing biochar adoption and household income among adopters and non-adopters. The model corrects for potential selection bias, recognizing that farmers who adopt biochar may differ systematically from those who do not. The Wald test of independence ($\chi^2 = 3.87$; $p = 0.049$) indicates significant correlation between the selection and outcome equations, confirming that unobserved factors jointly influence both adoption and welfare outcomes. Hence, using the ESR approach is justified. In totality, the results suggest that observed and unobserved factors together determine farmers' adoption of biochar and household income taken into consideration their biochar adoption decision.

Groundnut farm size is a positive and significant determinant of income among non-adopters at the 1% level. This implies that an increase in farm size will correspond to an increase in household income holding all else constant. The finding is in line with priori expectations because farmers with large farm holding are likely to produce in larger quantities and by implication, higher household income through economies of scale effects irrespective of farmers' adoption decisions. The significance among non-adopters suggests that farm size contributes more directly to household income through production volume rather than through adoption of biochar itself.

Also, Farmer age was found to be negative to farm household income of both biochar adopters and non-adopters but only significant at 5% level for adopters' household income. This finding suggests that older farmers irrespective of whether they adopt biochar or not would have lower household income compared to younger farmers. The results could be attributed to older farmers being weaker and prone to health challenges which limits the economic activities compared to younger farmers who are more energetic and have the capacity to adopt yield enhancing agricultural technologies including biochar which are labor demanding. Again, younger farmers are more likely to leverage on modern tools like social media to learn and access information that could enhance their productivity and by extension household income compared to older farmers.

Household size showed a positive coefficient to the household income of both biochar adopters and non-adopters but it was significant for adopters' household income. This implies that larger households are more likely to have higher income compared to smaller households. This finding is inconsistent with priori expectation because bigger household are likely to be constraint in terms of resource due to larger number of people who need to be catered for with the merger resource available, thus, may have a reducing effect on household income. However, bigger household size implies more family labour for both farm and off-farm activities. Therefore, if the household composition is more of active working force compare to dependents, higher household income is expected (Omotoso et al., 2018). This result is inconsistent with Tran et al. (2018) who found household size to be negatively related to household per capita income. The finding also contradicts that of Nguyen and Nguyen (2019) who reported household size as a negative function of household per capita income. However, the result is consistent with Zant (2022) who found household size to have positive effect on household income.

Again, distance to the district capital was significant for only non-biochar adopters' household income but positive to adopters' household income and negative to non-adopters' household income. This suggest that an additional kilometer from the district capital by a farmer will increase the household income of biochar adopters and decrease the income of non-biochar adopters hold all else constant. This finding resonates well with expectations because farmers who reside far from the district capital/ urban center are less likely to have access to market for fertilizer, improve seeds as well as market for their produce and even if they do, will be at a higher cost which will negatively affect their income. However, biochar has proven to be effective in increasing yield and also easy to produce in the rural areas due to the readily availability of biomass. Thus, farmers who capitalize on biochar for their groundnut production are likely to have higher yield and by implication higher household income.

NGO support emerged as a positive determinant of household income among biochar adopters and non-adopters but only significant for biochar adopters. The results suggest that farmers who receive NGO support are more likely to have higher household income devoid of whether of biochar adoption. This is in consonance with priori expectations because NGO support for farmers could be in the form of input subsidies, training on good agricultural practices, farm management as well as market linkage. These supports have the potential to increase farmers' productivity and also ensure that farmers sell at the most profitable price which could lead to higher household income.

Market access showed a positive effect on household income among both biochar adopters and non-adopters but only significant for non-adopters at 10% level, indicating that proximity to markets enhances farmers' income levels even in the absence of biochar adoption. Farmers with better access to markets are able to sell their produce at competitive prices, access production inputs more easily, and benefit from timely market information, all of which could translate to higher income.

Agricultural extension services variable was a positive function of both biochar adopters' and non-adopters' household income but only significant for non-biochar adopters' household income. This finding suggests that access to extension services enhances farmers' productivity and income, even in the absence of biochar adoption. Extension contact provides farmers with valuable knowledge on improved agronomic practices, pest and disease management, and resource-efficient input use, which collectively contribute to higher yields and by extension higher household income. This finding is line Onubuogu et al. (2014) and Olorunfemi et al. (2017) who found farmers with access to extension services to have higher income compared to farmers without extension access.

Credit access has a negative and significant effect on household income among adopters at 5% level of significance. This implies that while credit is intended to ease liquidity constraints and support production, it may not always translate into higher income. The negative relationship could stem from high interest rates, delays in credit disbursement, or misallocation of borrowed funds for consumption instead of productive purpose. Additionally, repayment obligations may offset the income gains from biochar use.

Table 4.3a: Determinants of biochar adoption and welfare (household income)

VARIABLES	*lnhhinc_1*	*lnhhinc_0*	*Biochar*
Education	-0.0373(0.171)	-0.0609(0.105)	-0.0674(0.226)
Groundnut farm size	0.0289(0.0304)	0.145***(0.0334)	0.0738(0.0606)
Farmer age	-0.0196**(0.00820)	-0.00687(0.00537)	-0.00306(0.0122)
Household size	0.0388*(0.0211)	0.0197(0.0158)	-0.0470(0.0333)
District capital dist	0.00381(0.00670)	-0.0162***(0.00553)	0.0245**(0.0106)
Seeds qty	0.00284(0.00237)	0.00188(0.00178)	0.00166(0.00339)
chemical qty	-0.00325(0.00230)	0.00841(0.0104)	0.00118(0.00570)
Market access	0.0583(0.298)	0.243*(0.142)	-0.475(0.313)
NGO Support	0.536***(0.141)	0.169(0.128)	0.338(0.212)
Remittances	0.160(0.136)	-0.169(0.128)	0.0363(0.195)
Agric extension	0.00904(0.136)	0.265**(0.118)	0.373*(0.197)
Credit access	-0.385**(0.168)	-0.0717(0.122)	0.157(0.237)
Distance input dealers	-0.0106(0.00674)	6.76e-05(0.00602)	-0.00179(0.0109)
Distance plot	-0.000738(0.00688)	0.0180**(0.00832)	0.0204*(0.0119)
FBO	-0.144(0.164)	0.0724(0.115)	0.195(0.231)
Married	0.420***(0.153)	-0.115(0.110)	-0.170(0.222)
Wa West (Based)			
JIRAPA	0.0285(0.177)	0.300**(0.143)	1.215***(0.292)
Lawra	-0.557*(0.294)	-0.913***(0.127)	-1.896***(0.283)
Sissala West	-0.356(0.312)	0.405*(0.245)	-1.285***(0.418)
Training on biochar			2.751***(0.273)
lns1	-0.330***(0.0498)		
lns2		-0.235***(0.0420)	
Rho1			0.00300(0.199)
Rho2			0.704***(0.235)
Constant	7.777***(0.889)	7.429***(0.449)	-3.245***(1.025)
Observations	564	564	564

Wald test of indep. eqns.: chi2(1) = 3.87 Prob > chi2 = 0.0490

The distance to the farm plot was negative to household income of biochar adopters and positive to non-adopters' household income but significant to the household income of non-adopters. This suggests that non-adopters with relatively distant plots tend to earn higher incomes, possibly because such plots are larger or more fertile compared to those close to homesteads. Alternatively, farmers may devote more effort and resources to distant plots to maximize productivity. The positive coefficient may also indicate that distant plots, often under less intensive cultivation, yield better returns when properly managed. During a respondent indicated that "*the nearby farms are less fertile so if you want to get good yield you have to go far*. Another farmer had this to say: "*I have seen significant improvement in my income since I* *started farm in the forest. Now I have been able to build my one bedroom. I spend less on fertilizer because the land is already fertile"*

Marital status was found to be positive and significant for biochar adopters' household income but negative and insignificant to non-biochar adopters' household income. Married farmers are likely to have more stable labour availability and greater resource-sharing opportunities within the household, which can enhance biochar application and farm productivity. Marriage may also facilitate joint decision-making and risk-sharing in the adoption of innovative practices. One of the respondents interviewed indicated that;" My *husband son has been helping me on my farm and my husband always make sure all good agricultural practices are implemented on my farm as he does on his farm"*

Jirapa showed a positive coefficient for both biochar adopters and non-adopters household income but only significant for non-adopters' household income. This implies that farmers in Jirapa irrespective of whether they adopt biochar or otherwise, will have higher household income compared to farmers in Wa West. On the contrary, farmers in Lawra were found to have lower income compared to farmers in Wa West irrespective of biochar adoption or otherwise. However, the results showed a negative coefficient for biochar adopters' household income and a positive coefficient for non-adopters' household income but only significant for non-adopters' household income and vice versa for farmers in Wa West district. These spatial differences highlight the influence of local conditions, institutional networks, and project activities on both adoption behavior and household income.

4.6.2. Correlates of biochar adoption and household per *household expenditure*

Table 4.3b presents determinants of biochar adoption and expenditure of both biochar adopters and non-adopters in the Upper West Region using the ESR model. The likelihood ratio test for joint independence was significant at 5% level. Suggesting a rejection of the null hypothesis that the three equations are jointly independent and should be estimated separately. Also, the "rho" was positive and significant for biochar adopters signifying a rejection of the null hypothesis of no selectivity bias. This implies that unobserved factors jointly determine biochar adoption and welfare (Expenditure). Thus, the ESR model is appropriate for the analysis. Overall, the analysis connotes that both observed and unobserved factors jointly determine farmers adoption of biochar and household expenditure taking into account their biochar adoption decisions.

Household size is a positive and statistically significant determinant of household expenditure among non-biochar adopters at the 5% level but negative and insignificant to household expenditure among adopters. This implies that an increase in household size will translate to an increase in household expenditure. Larger households typically have greater consumption needs, including food, clothing, education, healthcare, and other essential goods and services. This finding is in consonance with literature that larger households is expected to have more food expenditure than smaller households, since additional members leads to resource constraint, given scarcity of resource (Tingum and Kuponiyi, 2020). Siman et al. (2020) report that household size does not significantly influence overall household consumption, suggesting that the effect of household size may vary depending on context, income sources, and consumption structure. Hastuti et al. (2021) found that while household size does not significantly affect food consumption alone, it has a significant effect on non-food and combined food and non-food expenditures, indicating that larger households tend to allocate more resources to non-food needs such as education, housing, and healthcare. Marisennayya (2019) found family size and disposable income as direct determinants of household consumption expenditure. Similarly, Nguyen (2020) revealed that the per capita consumption of households is explained by household size and other factors. Family composition also positively affects food expenditure specifically when most of the household members are dependent (Kearney, 2019; Zani et al., 2019)

Also, the results indicate that distance from the district capital negatively influences household expenditure among biochar adopters and non-adopters' household expenditure but only significant to biochar adopters' expenditure. The negative association with household expenditure suggests that farmers residing farther from the district capital tend to spend less overall. This may be attributed to several factors. First, the cost of living, particularly food prices, is generally lower in rural areas compared to the district capitals, where market demand and transaction costs are higher. Second, farmers in remote areas often rely on self-produced food and locally available inputs such as organic manure, compost or biochar, which reduces their expenditure on purchased farm inputs and by implication overall household expenditure.

Seed quantity exhibits a positive and significant association with household expenditure for non-biochar adopters at 5 percent level. The results implies that an increase in the quantity of seeds used will lead to an increase household per capita consumption expenditure. The results in plausible because improved seeds are purchase, thus every kilogram of seed comes at additional cost. Again, an increase in the quantity of seed use is likely to translate to higher yield and farm income and by extension, higher household expenditure. Kaliba and Mazvimavi (2021) revealed that adoption of improved sorghum varieties in Tanzania significantly increases household income, consumption expenditure, and overall wealth. Ahmed et al. (2016) also found seed quantity to have significant improvements in household welfare, measured in terms of expenditure per adult equivalent.

On the contrary, quantity of chemical use showed a negative and significant relation with consumption expenditure for both adopters and non-adopters. This implies that an increase in chemical use will result in a decrease in household consumption expenditure. The negative effect on consumption expenditure can be explained because farmers who use chemical reduce labour requirement on the farm which is a major cost component in production, thus the reducing effect on expenditure.

Furthermore, NGO support was found to be positively related to household expenditure among both biochar adopters and non-adopters but only significant to household expenditure among non-adopters. The finding is in line with priori expectations because NGOs often provide training, input subsidies, and financial linkages that boost farm income and by implication, household expenditure. The strong positive association implies that institutional support remains crucial for household expenditure, especially where market and extension systems are weak irrespective of biochar adoption or otherwise. Rooderick et al. (2016) noted that NGO assistance significantly reduces both the incidence and depth of poverty, underscoring the effectiveness of such interventions in improving household welfare outcomes.

Table 4.3b: Determinants of biochar adoption and welfare (household expenditure)

VARIABLES	lnExpenditure_1	lnExpenditure_0	Biochar
Edu	-0.257(0.163)	0.148(0.0949)	-0.0291(0.212)
Groundnut size	0.0342(0.0252)	0.0446(0.0299)	0.0452(0.0494)
Farmer age	-0.00694(0.00753)	0.000541(0.00485)	-0.00660(0.00968)
Household size	-0.0192(0.0164)	0.0343**(0.0161)	-0.0394(0.0263)
District capital dist	-0.0109*(0.00631)	-0.00242(0.00519)	0.0288***(0.00950)
Seeds qty	0.00175(0.00210)	0.00302**(0.00153)	0.00260(0.00377)
chemical qty	-0.000135(0.00134)	-0.0124*(0.00693)	0.000960(0.00343)
Market access	-0.307(0.202)	-0.533***(0.130)	-0.249(0.298)
NGO Support	0.0556(0.123)	0.544***(0.132)	0.265(0.225)
Remittances	-0.0236(0.119)	-0.0365(0.107)	0.0945(0.213)
Agric extension	0.582***(0.132)	0.379***(0.103)	0.498**(0.207)
Credit access	0.494***(0.135)	0.441***(0.109)	0.184(0.247)
Dist input dealers	-0.00393(0.00596)	-0.0151***(0.00502)	-0.00392(0.00891)
Dist plot	0.0130**(0.00616)	0.0178**(0.00706)	0.0180(0.0131)
FBO	0.0363(0.168)	-0.0328(0.109)	0.230(0.257)
Married	0.575***(0.141)	0.173*(0.0903)	-0.184(0.211)
Wa West (Based)			
JIRAPA	-0.0958(0.134)	-0.0553(0.130)	1.257***(0.332)
Lawra	-0.668**(0.335)	-0.270**(0.110)	-2.019***(0.302)
Sissala West	0.136(0.273)	0.0318(0.227)	-1.474***(0.379)
Training on biochar			2.802***(0.253)
lns1	-0.493***(0.0982)		
lns2		-0.386***(0.0636)	
r1			0.224*(0.118)
r2			-0.266(0.189)
Constant	7.375***(0.656)	7.233***(0.433)	-3.894***(0.985)
Observations	564	564	564

LR test of indep. eqns. : chi2(1) = 8.92 Prob > chi2 = 0.0028

Additionally, the results reported in Table 4.3b indicate a positive and statistically significant relationship between access to agricultural extension services and farm household expenditure. This relationship holds irrespective of biochar adoption status, suggesting that farmers who benefit from extension support tend to exhibit higher levels of household expenditure compared to those without access to such services. The finding is expected because access to extension facilitates knowledge acquisition and adoption of modern and sustainable agricultural technologies including biochar, thereby improving productivity and income and by extension, per capita expenditure.

Tamirat and Abafita (2021) showed that access to extension services significantly influences technology adoption decisions, with adopters achieving higher crop yields and household expenditure relative to non-adopters. Similarly, Belay and Mengiste (2021) demonstrate that extension visits are a key determinant of agricultural technology adoption and that adoption has a direct and significant effect on increasing household consumption expenditure.

More so, credit access demonstrated positive and significant effect on the per capita expenditure of groundnut farm household per capita consumption expenditure holding all factors constant. This means that farmers who have access to credit are more likely to have higher per capita expenditure devoid of biochar adoption compared to farmers who do not have access to credit. This conforms to priori expectations because credit access is likely to alleviate liquidity constraints, enabling farmers to spend on consumption and invest in productivity-enhancing inputs and technologies which could translated to higher yield and income and by extension per capita expenditure. Tamirat and Abafita (2021) show that access to credit significantly influences farmers' decisions to adopt row planting technology in Ethiopia, with adopters experiencing substantially higher crop yields and household expenditure. Similarly, Belay and Mengiste (2021) find that credit access is a major determinant of agricultural technology adoption and that such adoption has a direct and significant impact on increasing household consumption expenditure while simultaneously reducing poverty.

Moreover, distance to the nearest input dealer revealed was found to be a negative function to consumption expenditure. This suggests that farmers who are far from input dealers have lower consumption expenditure compared their counterparts who are closer. This contradicts priori expectations because being closer to input dealers is associated with lower transactional costs, thus, farmers far are likely to spend more. However, farmers who are far usually have large tracks of fertile farm lands that require little to no inputs, again, most of their consumables and produced by themselves, likely to have lower expenditure. In addition, distance to farm plots was positively associated with household per capital expenditure for both adopters and non-adopters, although the effect was small. This suggests that farmers with distant plots may cultivate larger or more fertile lands, thus may have higher yields and incomes which could trigger higher spending compared to their counterparts who are closer.

Marital status was positively and significantly associated with household expenditure. This implies that being married correspond to higher consumption expenditure holding all other factors constant. The results imply that, being married leads to an increase in household consumption expenditure. This could be attributed to fact that married consumers have more mouths to feed compared to their counter parts who are not married. The result corroborates with those from previous studies which arrived at similar positive causal-effect between marital status and food expenditure (Cheah et al., 2021; Donkoh et al., 2012; Kilima, 2020; Mbwana et al., 2016)

Finally, the locational effects captured by district-level indicators reveal a negative and statistically significant effect on per capita household expenditure for both biochar adopters and non-adopters residing in the Lawra District, relative to the reference district (Wa West). This finding indicates that, all else being equal, households in Lawra exhibit lower consumption expenditure compared to their counterparts in Wa West, suggesting the presence of pronounced spatial disparities in welfare outcomes across districts. These spatial differences are likely driven by variations in local agro-ecological conditions, market access, infrastructure quality, and the strength of institutional and development interventions.

4.7. Effects of biochar adoption on welfare

The results in Table 4.3c below show that biochar adopters would have an average household per capita expenditure of GH₵10.03 if the adopt biochar and GH₵9.06 if they had not adopted biochar, generating an ATT of GH₵0.97 which is the loss for not adopting biochar. On the other hand, farmers expect a per capital expenditure of GH₵8.33 if they actually did not adopt biochar and GH₵8.38 if they decide to adopt, given an ATU of GH₵0.05 at 5% level of significance. Overall, the difference between the ATT (the lost if they decide not to adopt) and ATU (the gain if they decide to adopt) is positive, implying that adoption enhances household welfare.

Table 4.3c: Effects of biochar adoption on welfare

	Yes	*No*	*Treatment*	*St Err*	*diff*	*St Err*
Household per capita expenditure						
Adopter	10.034	9.062	ATT=0.972***	.086	0.927***	0.090
Non-adopter	8.376	8.330	ATU= 0.046**	.019		
Household per capita income						
Adopter	9.662	8.719	ATT=0.944***	.104	0.890***	0.087
Non-adopter	8.048	7.994	ATU=0.054*	.028		

Similarly, as illustrated in Table 4.3c above, biochar adoption exhibits a significant positive effect on household per capita income. Adopters record an average per capita income of GH₵9.66 if the actually adopt compared to GH₵8.72 if adopters had decided not to adopt, yielding an ATT of GH₵0.94. For non-adopters, per capita household income increased from GH₵8.00 to GH₵8.05 given an ATU of GH₵0.05 if they had adopted, this implies that non-adopters would have gain by adopting biochar.

Overall, the results showed a positive relationship between biochar adoption and household welfare. This implies that encouraging farmers to adopt biochar in their production will translate to better welfare outcomes holding all else constant. In line with this finding is Torsu et al. (2024) who reported that adoption of greenhouse technologies as a CSA practice increased per capita consumption expenditure among smallholder vegetable farmers by approximately 13 percent. The result also aligned with those of Awotide et al. (2022) and Mujeyi et al. (2021) who found that adoption of climate-smart agricultural technologies significantly improves multiple dimensions of household welfare, including per capita food and non-food expenditures as well as total household income. Moreso, Okyere and Kornher (2023) found participation in carbon farming to have statistically positive effect on farm household welfare.

4.8. Parameter estimates for the conventional and sample selection SPF models

Tables 4.4a and 4.4b show the results of the conventional and sample selection SPF models for unpaired and matched samples, respectively. The null hypothesis of the variance parameter for compound error (λ=0) is rejected at the 1% level, indicating that technical inefficiency is a significant contributor to variability in observed yield. The pooled model for both samples shows a positive and substantial influence of biochar adoption on groundnut yield, which supports the previous conclusion. The sample selection SPF model found statistical support for selection bias related to unobserved qualities, as indicated by a significant ρ for biochar adopters' specifications in both subsamples (Table 4.4a and 4.4b). This implies the presence of selection bias occasioned by latent factors, and adopting the selection bias-corrected SPF model over the conventional SPF model correct to avoid biased estimates (Asmare et al. 2022; Bravo-Ureta et al., 2021).

Table 4.4a and Table 4.4b present the determinants of groundnut yield conditional on biochar adoption. As shown, the analysis demonstrated positive partial elasticities across both SPF models for unmatched and matched samples. The partial elasticity assesses the percentage change in each input to the percentage change in groundnut yield. Apart from seed variety, all inputs including land, seed, chemical, fertilizer, labour and soil quality were positively and significantly associated with groundnut yield. This implies that an increase in these inputs is associated with higher groundnut yield, underscoring the significance of resource use intensity on groundnut yield among smallholder farmers.

Among the conventional inputs, labour demonstrated the highest contribution to groundnut yield across both models and samples contrary to (Abdul-Rahaman et al., 2022; Abdul-Rahaman and Abdulai, 2018). The finding also departs from the argument of declining marginal benefits associated with labour occasioned by the abundance of balour in the study area (Gonzalez-Flores et al., 2014).

In addition, in both models and samples, chemicals contribute the second most to groundnut output across both farmer types. Previous studies have revealed similar findings (Abdul-Rahaman et al., 2022; Abdul-Rahaman et al., 2021; Abdul-Rahaman and Abdulai, 2018; Anang et al., 2016). The findings are also consistent with previous research in underdeveloped countries (Bravo-Ureta et al., 2012; Jayne et al., 2014), showing that purchased inputs play an important role in increasing agricultural yields. We also discovered that fertilizer had a favorable and substantial effect on groundnut yield across both models and data, which agrees with Addison et al. (2016).

Furthermore, land is positively and significantly associated with groundnut yield, implying a 1% change in land size is associated with a larger percentage change in groundnut yield. However, the effect of land on groundnut yield is much higher for non-biochar adopters compared to adopters across samples. This implies that non-biochar adopters' output depends heavily on land expansion while biochar adopters have comparatively higher yield per unit land corroborating with Azumah and Azawla (2017). In a similar vein, Addison et al. (2016), Kea, Li, and Pich (2016), and Donkor and Owusu (2014) also reported land size as a positive function of rice output in their respective studies.

Moreover, seed showed the least positive and significant effect on groundnut yield, though only significant for non-adopters in all both models and samples consistent earlier findings (Anang et al., 2016; Nkebge 2012). However, the finding deviates from Azumah et al. (2019) who reported seed as an inverse function of rice output.

Aside the conventional inputs, other factors that enhance groundnut yield include soil quality and locational dummies. In particular, the parameter estimate for soil quality is positive and significant across models and samples, signifying that groundnut farms that are highly perceived to be fertile correspond to higher groundnut yield compared to farms that are perceived to be less fertile corroborating with (Abdul-Rhaman et al., 2021). A deeper look at the results also revealed that the contribution of soil quality to groundnut yield favored biochar adopters for both samples and models. The finding is in conformity with that of Abdul-Rahaman et al. (2022) who found fields of highly perceived soil quality generating higher value of vegetable production.

Finally, relative to Wa East destrict (reference district), a higher groundnut yield is associated with farms located in Jirapa, Lawra, and Sissala West. This finding demonstrates the importance of location-fixed effect, particularly in accounting for disparity in extension support, soil characteristics, input and information access, neighborhood effects and environmental conditions.

Table 4.4a: Parameter estimates for the conventional and sample selection SPF models: Unmatched sample

Variables	Conventional SPF						Sample selection SPF			
	Pooled		Adopters		Non-adopters		Adopters		Non-adopters	
	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E
Constant	5.417***	0.311	4.974***	0.561	5.356***	0.392	4.932***	0.656	5.063***	0.542
ln land	0.495***	0. 069	0.396***	0.127	0.561***	0.085	0.380**	0.154	0.566***	0.076
ln seed	0.022	0. 018	0.021	0.035	0.040*	0.022	0.022	0.042	0.039*	0.023
ln fertilizer	0.454***	0.059	0.167***	0.010	0.116***	0.011	0.170***	0.010	0.117***	0.013
ln chemical	0.590***	0. 042	0.259***	0.060	0.226***	0.077	0.191***	0.069	0.260***	0.098
ln labor	0.731***	0.017	0.695***	0.028	0.586***	0.026	0.850***	0.036	0.561***	0.023
Fertilizer dummy	0.205***	0.029	0.856***	0.054	0.433***	0.035	0.882***	0.064	0.894***	0.046
Chemical dummy	0.311***	0.102	0.463***	0.168	0.479***	0.145	0.451**	0.207	0.417**	0.174
Soil quality	0.107*	0.061	0.320**	0.124	0.153**	0.071	0.351**	0.157	0.191**	0.087
Seed variety	0.109*	0.062	0.113	0.124	0.006	0.075	0.137	0.154	0.031	0.084
Jirapa	0.622***	0.074	0.801***	0.122	0.535***	0.095	0.797***	0.164	0.561***	0.109
Lawra	0.182**	0.075	0.373**	0.173	0.083	0.088	0.351*	0.187	0.067	0.107
Sisala West	0.084	0.123	0.406**	0.180	0.348**	0.170	0.380**	0.141	0.252	0.180
Biochar adoption	0.138**	0.062	-	-	-	-	-	-	-	-
L. Likelihood	-513.56		-185.04		-316.18		-262.34		-391.29	
λ	1.123***	0.114	1.378***	0.213	1.032***	0.139	-	-	-	-
σ^2	0.751***	0.001	0.796***	0.003	0.708***	0.002	-	-	-	-
$\sigma_{(u)}$	-	-	-	-	-	-	0.637***	0.140	0.446***	0.163
$\sigma_{(v)}$	-	-	-	-	-	-	0.472***	0.057	0.521***	0.048
$\rho_{(w,v)}$	-	-	-	-	-	-	0.459***	0.130	-0.404*	0.207
N	564		202		362		202		362	

Note: *, **, *** represent significance at 10%, 5%, and 1% levels, respectively.

Table 4.4b: Parameter estimates for the conventional and sample selection SPF models: Matched sample

Variables	Conventional SPF							Sample selection SPF			
	Pooled		Adopters			Non-adopters		Adopters		Non-adopters	
	Coeff.	S.E	Coeff.	S.E	h	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E
Constant	5.547***	0.348	4.585***	0.862		5.356***	0.392	4.618***	0.705	5.064***	0.537
ln land	0.493***	0. 073	0.381***	0.139		0.561***	0.085	0.326*	0.185	0.567***	0.075
ln seed	0.020	0. 018	0.048	0.035		0.040*	0.022	0.049	0.047	0.039*	0.023
ln fertilizer	0.429***	0.067	0.269***	0.016		0.116***	0.011	0.243***	0.013	0.117***	0.013
ln chemical	0.702***	0. 045	0.369***	0.060		0.226***	0.077	0.260***	0.061	0.260***	0.098
ln labor	0.729***	0.018	0.683***	0.031		0.586***	0.026	0.843***	0.034	0.561***	0.023
Fertilizer dummy	0.208***	0.031	0.843***	0.055		0.433***	0.035	0.871***	0.060	0.894***	0.046
Chemical dummy	0.288***	0.107	0.424***	0.169		0.479***	0.145	0.490**	0.205	0.417**	0.174
Soil quality	0.108*	0.064	0.321**	0.146		0.153**	0.071	0.334**	0.149	0.191**	0.087
Seed variety	0.107*	0.064	0.116	0.138		0.006	0.075	0.125	0.141	0.031	0.084
Jirapa	0.632***	0.079	0.793***	0.128		0.535***	0.095	0.753***	0.198	0.561***	0.109
Lawra	0.199**	0.077	0.513***	0.177		0.083	0.088	0.463	0.384	0.067	0.107
Sisala West	0.118	0.127	0.532***	0.172		0.348**	0.170	0.484***	0.143	0.252	0.180
Biochar adoption	0.135**	0.067	-	-		-	-	-	-	-	-
L. Likelihood	-457.94		-185.04			-316.18		-203.05		-382.80	
λ	1.33***	0.133	1.382***	0.210		1.032***	0.139	-	-	-	-
σ^2	0.783***	0.001	0.792***	0.005		0.708***	0.002	-	-	-	-
$\sigma_{(u)}$	-	-	-	-		-	-	0.957***	0.147	0.440***	0.168
$\sigma_{(v)}$	-	-	-	-		-	-	0.302***	0.102	0.525***	0.049
$\rho_{(w,v)}$	-	-	-	-		-	-	0.428***	0.128	-0.443**	0.219
N	505		143			362		143		362	

Note: *, **, * represent significance at 10%, 5%, and 1% levels, respectively.**

4.8.1. Technical efficiency of Biochar Adopters and Non-adopters across SPF levels

Table 4.5 shows the results of the group-specific TE, TGR, and MTE scores for biochar adopters and non-adopters in both matched and unmatched samples, as calculated using conventional and selection bias-corrected SPF models. The mean difference between biochar adopters and non-biochar adopters in terms of TE, TGR, and MTE was calculated using a t-test, as shown in Table 4.5. Across samples, there are significant mean differences between biochar adopters and non-adopters in terms of TE and TGR for both models. For the standard SPF model in the unpaired sample, biochar adopters and non-adopters had TE scores of 67% and 61%, respectively. However, the selection bias-corrected SPF model revealed that both biochar and non-biochar adopters operated at TEs of 70% and 62%, respectively. This research suggests that adopters do better within their cohort than non-adopters. The results also show an increase in TE scores after controlling for biases caused by unobservable farmer characteristics in both populations.

Table 4.5 shows the TGR and MTE scores for all models and samples. In the mismatched sample, the selection bias-corrected SPF model estimate demonstrates that biochar adopters had a greater TGR (88%) than non-adopters (85%). Furthermore, the TGRs for biochar adopters and non-adopters were 88% and 87%, respectively, in the matched group, while the difference was not statistically significant. The findings imply that biochar adopters are more likely to use the finest technology than non-adopters. Furthermore, in the mismatched sample, the MTE score obtained from the selection bias-corrected model for biochar adopters is significantly higher (62%) than that of non-adopters (53%). The matched sample yielded similar results for adopters (62%) and non-adopters (47%). However, in the matched population, there was no statistically significant difference in mean MTE scores between biochar adopters and non-adopters. The fining implies that biochar adopters outperform non-adopters in yield and efficiency.

Table 4.5: Technical efficiency of Biochar Adopters and Non-adopters across SPF levels

Item	Conventional SPF						Test of means	Sample Selection SPF				Test of means
	Pooled		Adopters		Non-adopters			Adopters		Non-adopters		
	Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Unmatched Sample												
Technical Efficiency (TE)	0.65	0.11	0.67	0.10	0.61	0.13	6.11***	0.70	0.08	0.62	0.13	9.03***
Technology Gap Ratio (TGR)	0.92	0.04	0.93	0.03	0.92	0.04	3.35***	0.88	0.05	0.85	0.09	5.09***
Metafrontier Technical Efficiency (MTE)	0.60	0.10	0.61	0.10	0.60	0.11	1.09	0.62	0.08	0.53	0.12	10.64***
Matched Sample												
Technical Efficiency (TE)	0.63	0.13	0.67	0.10	0.55	0.19	9.21***	0.71	0.08	0.54	0.19	14.15***
Technology Gap Ratio (TGR)	0.93	0.03	0.94	0.03	0.93	0.04	3.05***	0.88	0.06	0.87	0.08	1.52
Metafrontier Technical Efficiency (MTE)	0.58	0.12	0.60	0.13	0.58	0.12	1.59	0.62	0.08	0.47	0.17	13.44

Note: *** represents significance at 1% level. SD: Standard Deviation

4.8.2. Predicted frontier groundnut output for biochar adopters and non-adopters

The study further assessed the performance of biochar adopters and non-adopters by predicting the frontier groundnut output for cases without bias-correction (unmatched) and with bias correction (matched). As illustrated in Table 4.6, farmers adoption of biochar positively and significantly contributed to 42% and 46% increase in the predicted frontier groundnut output with and without selection bias correction respectively. The higher percentage obtained in the matched sample suggests that controlling for latent heterogeneity and selection bias enhances the estimated output effect of biochar adoption. More importantly, across both models and samples, biochar adopters exhibited higher frontier groundnut output compared to non-adopters. The results in totality provide robust support that biochar adoption strongly enhances frontier-level groundnut output, reinforcing the earlier efficiency findings and highlighting the role of biochar as a yield enhancing technology in groundnut production.

Table 4.6: Predicted frontier groundnut output for biochar adopters and non-adopters

SPF model	Pooled	Adopters	Non-adopters	% change in predicted output	Test of means [a]
Unmatched Conventional					
Mean	535.35	753.59	440.31	41.57	8.70***
Minimum	217.91	281.26	219.73		
Maximum	1640.06	1847.46	2027.21		
Matched Sample selection					
Mean	584.58	810.64	439.52	45.78	8.50***
Minimum	215.16	302.03	213.29		
Maximum	1713.55	2560.41	2408.79		

*** represents significance at 1%level.

[a] *t* test of predicted mean frontier output difference between biochar adopters and non-adopters

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

Agricultural sector has a formidable twofold challenge of producing twice the world food by 2050 to sustain the world population and at the same time fight the impacts of climate change and reduce emission of its greenhouse gases by adopting sustainable agricultural methods. This research evaluates the impacts of biochar adoption on commercialization, welfare and productivity of farm households with cross-sectional information collected among 564 farmers in four sampled districts in the Upper West Region, through a multistage sampling method and semi-structured questionnaires. The data was analyzed using recursive bivariate probit model, endogenous switching regression model and sample selection SPF model. The key findings of the estimation of the data are summarized in the proceeding paragraphs.

The study results indicated that institutional factors, locational specific conditions, and farming characteristics influence the decision of the farmers to adopt biochar. Planting in larger farms, increased number of seeds and pesticides, availability of credit facilities and training in production of biochar increases the adoption of biochar. Conversely, the bigger the household size and access to market, the less the likelihood of biochar adoption.

The analysis also revealed that biochar adoption has a good and significant impact on commercialization of farmers. Biochar users are quite more likely to sell a part of the groundnut harvest as compared to those who have not adopted, a trend that can be explained by increased level of production, high yield consistency, and reduced market entry barriers. The implication of this association is that soil-enhancing technologies may be deployed in order to realize commercialization, thereby contributing to the gradual transformation of smallholder agriculture into market-oriented production.

Furthermore, the results showed that biochar adoption is positively and significantly associated with farm household welfare measured by income and consumption expenditure per capita.

In terms of productivity and efficiency, the stochastic frontier results provide strong empirical support for the yield-enhancing and efficiency-improving effects of biochar. Adopting farmers consistently demonstrate higher levels of technical efficiency, operate closer to the production frontier, and achieve superior metafrontier efficiency relative to non-adopters, even after adjusting for selection bias. Notably, biochar users obtain higher yields per unit of land, suggesting that productivity gains arise from sustainable intensification rather than expansion of cultivated area.

Across the various analytical components, the findings emphasize the significance of enabling institutional and infrastructural conditions. Access to extension services, credit facilities, and NGO support is closely linked to improved welfare outcomes, whereas greater distance from markets and input suppliers limits both adoption decisions and household expenditure levels. Moreover, observed differences across districts reflect variations in institutional presence and project coverage, underscoring the importance of spatially targeted development interventions in shaping technology uptake and its impacts.

5.2 Conclusions

The findings indicate that the use of biochar substantially increases farmers' engagement with output markets. Even after correcting for potential endogeneity, farmers who adopt biochar are significantly more likely to sell their produce than their non-adopting counterparts. This outcome reflects the role of biochar in boosting production levels, improving yield reliability, and reducing the effective costs and risks associated with entering output markets. The results therefore support the argument that soil fertility–enhancing technologies can act as critical enablers in shifting smallholder agriculture away from subsistence production toward greater market orientation.

In addition to its commercialization effects, biochar adoption is associated with notable improvements in household welfare. Evidence from the endogenous switching regression and treatment effects estimations shows that adopting households attain significantly higher per capita expenditure and income than they would have achieved had they not adopted the technology. The size and statistical robustness of the Average Treatment Effect on the Treated suggest that biochar adoption translates into meaningful gains in living standards, allowing households to allocate more resources to food consumption, schooling, healthcare, and other basic needs. While households that have not yet adopted biochar are also projected to experience welfare gains if they do so, the smaller Average Treatment Effect on the Untreated highlights the importance of initial resource endowments, managerial ability, and access to complementary services in determining the scale of benefits realized.

The results from the productivity and efficiency analyses further strengthen these welfare-related conclusions. Estimates from the stochastic frontier models reveal that biochar adoption significantly raises groundnut yields, even after accounting for selection bias linked to unobserved characteristics. Adopters consistently demonstrate higher levels of technical efficiency, operate closer to the production frontier, and record better metafrontier efficiency than non-adopters. Importantly, the evidence suggests that productivity gains among adopters are driven primarily by yield-improving intensification rather than by expanding cultivated land, implying that biochar supports more sustainable forms of production growth. The marked increases in predicted frontier output for adopters provide compelling evidence that biochar enhances both actual and potential production capacity.

The study also emphasizes the importance of complementary conditions in determining both adoption outcomes and welfare impacts. Access to extension services, financial resources, markets, and support from non-governmental organizations is found to significantly raise household income and expenditure irrespective of adoption status, whereas greater distance from markets and input suppliers negatively affects welfare. These findings make clear that biochar adoption does not generate benefits in isolation; instead, its effectiveness is considerably strengthened when supported by favorable institutional, financial, and market environments.

5.3 Recommendations

The findings of this study provide compelling evidence on the transformative potential of biochar adoption for smallholder groundnut farmers in the Upper West Region. By enhancing household welfare, improving farm productivity, and increasing technical efficiency, biochar emerges as a viable climate-smart agricultural technology with both economic and environmental benefits. In light of these results, the following recommendations are proposed to guide policy, practice, and future research.

First and foremost, strengthening agricultural extension services is paramount, as access to extension and training significantly influences biochar adoption and household welfare. Extension programs should incorporate practical demonstrations, participatory learning approaches, and farmer field schools to enhance knowledge on biochar production, appropriate application, and long-term soil fertility benefits. Tailored training interventions will enable farmers to adopt biochar more effectively and integrate it with other sustainable land management practices.

Access to credit and financial services is a critical enabler for biochar adoption. Many smallholder farmers face liquidity constraints that limit their ability to invest in biochar, quality seeds, and complementary inputs. Financial institutions, in partnership with development agencies, should design flexible credit schemes, including group-based lending and value-chain financing, to reduce barriers and support smallholder investment in productivity-enhancing technologies.

The study highlights the importance of improving rural market access. Distance from district capitals and input suppliers negatively affects household expenditure and adoption rates. Investments in feeder roads, local aggregation centers, and market infrastructure will reduce transaction costs, facilitate access to inputs, and allow farmers to translate productivity gains into higher incomes. Supporting farmer-based organizations and cooperative marketing arrangements will further strengthen market integration and bargaining power.

Community-based biochar production systems offer practical solutions to labor, cost, and scale challenges faced by individual farmers. Such collective production initiatives can ensure quality control, reduce production costs, and expand access to biochar. Local governments, research institutions, and development agencies should play a facilitative role by providing technical guidance, initial support, and monitoring frameworks to ensure agronomic effectiveness and sustainability. Spatial disparities in adoption and welfare outcomes underscore the need for location-specific interventions. Districts with limited institutional presence or weaker NGO support should be prioritized, with strategies tailored to local agroecological and socio-economic contexts. Decentralized policies that reflect the heterogeneity of smallholder farming systems will optimize adoption and welfare gains across the region.

Biochar adoption also enhances commercialization, suggesting that interventions should promote its role not only in soil fertility but also in market participation. Linking adopters to input and output markets, processors, and buyers through value-chain development initiatives will improve income, profitability, and household welfare. Finally, sustained monitoring, evaluation, and research are essential. While this study demonstrates short- and medium-term benefits of biochar adoption, further longitudinal studies are needed to assess its long-term impacts on soil health, yield stability, and environmental sustainability. Continuous research and adaptive management will provide evidence to guide policies, enhance adoption, and ensure that scaling biochar contributes to resilient and inclusive agricultural development.

5.4. Future Research Directions

While this study provides robust evidence on the benefits of biochar adoption, several avenues for future research remain. Longitudinal studies are needed to assess the long-term effects of biochar on soil health, nutrient cycling, and yield stability under varying climatic and soil conditions. Comparative studies across different agroecological zones could provide insights into location-specific adoption dynamics and welfare outcomes.

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APPENDIX 1

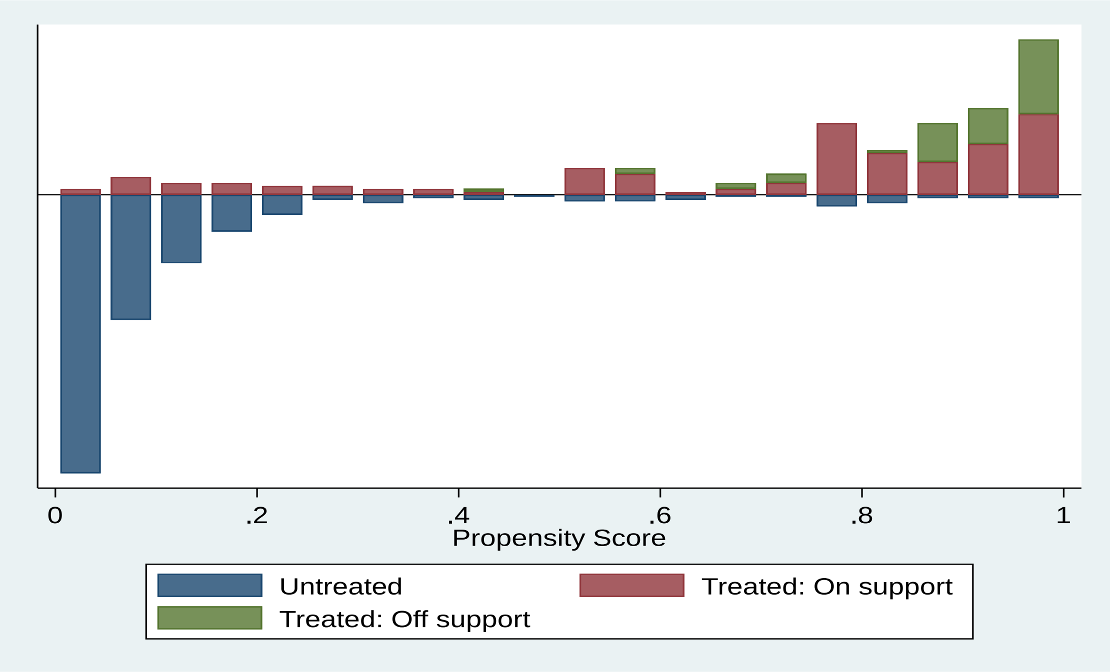

Fig. 1 Density of propensity scores for adopters and non-adopters of biochar

(Note: 59 observations fall outside the common support region)

```
   test $iv

   1)  [Biochar]Train_biochar = 0
   2)  [Biochar]o.Aware_biochar = 0
       Constraint 2 dropped

           chi2(  1) =   59.48
         Prob > chi2 =    0.0000

.  test $iv

 ( 1)  [CI]Train_biochar = 0
 ( 2)  [CI]Aware_biochar = 0

           chi2(  2) =    1.49
         Prob > chi2 =    0.4756
```

APPENDIX 2: QUESTIONNAIRE

UNIVERSITY FOR DEVELOPMENT STUDIES

FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCES

DEPARTMENT OF FOOD AND AGRICULTURAL ECONOMICS

QUESTIONNAIRE

Project Title: Biochar Adoption and its Implications on Farm Performance and Welfare among smallholder groundnut Farmers in Upper West Region of Ghana

Section A: socioeconomic and institutional characteristics of farmers

Part A: Socio-Demographic Characteristics

Questions	*Responses*
1. Are you the household head (HH)?	(1) Yes [ ] (2) No [ ]
2. Age of the farmer	
3. Age of HH (completed years of life)	
4. Gender of HH	(1) Male [ ] (2) Female [ ]
5. Marital status of HH	(1) Married [ ] (2) Single/divorced [ ] (3) Widow [ ]
6. Household (HH) size	
7. Farmer's experience (years) in own farming activities	
8. Farmer's experience (years) in cultivating groundnut on his own?	
9. Highest level of education completed by the respondent	(1) Primary school [ ] (2) JHS/MSLC [ ] (3) SHS [ ](4) Tech/Voc. [ ] (5) Training/Poly/Univ. [ ] 6) No education
10. Number of years of schooling of the farmer	………………………..
11. What kind of farmland holding/ownership do you practice	Owned [yes/no] Area in acre ----- Rented [yes/no] Area in acre ---- Family [yes/no] Area in acre ----- Others, specify……………………
12. Do you engage in any non-farm income generating activity?	Yes [ ] No [ ]
13. If yes, to the above question, what types of non-farm activities do you engage?	1. Trading (yes/no) 2. Permanent employee (Yes/no) 3. Casual labour (yes/no) 4. Driving or transport related businesses (Yes/No) 5. Others (Specify)

14. Who in the household is involved in…	
a. Management of groundnut	Man Yes [ ] No [ ] Woman Yes [ ] No [ ] Both Yes [ ] No [ ]
b. Decision making on planting material of groundnut	Man Yes [ ] No [ ] Woman Yes [ ] No [ ] Both Yes [ ] No [ ]
c. Involved in the sales of groundnut	Man Yes [ ] No [ ] Woman Yes [ ] No [ ] Both Yes [ ] No [ ]
d. In control over revenue gained from groundnut	Man Yes [ ] No [ ] Woman Yes [ ] No [ ] Both Yes [ ] No [ ]

15. Has any of the household members migrated from the community for more than 6 months in the last 12 months? 0 No [ ] 1 Yes [ ]
16. If yes, how many people? ……………………………………
17. Has any of the household members been sick of a chronic illness for more than 6 months in the last 12 months? 0 No [ ] Yes [ ]
18. What is your main source of income? 1 Agriculture [ ] 2 Others [ ]

Part B: Some institutional factors

1. Do you belong to an agricultural association? 0 No [ ] 1 Yes [ ]
2. If yes, how many agricultural associations do you belong to? ……………………
3. Do you attend association meetings? 0 No [ ] 1 Yes [ ]
4. How many times did you attend meetings during the 2023/2024 season? ………
5. What activities is the association engaged in? [ ] 1 Discussions on groundnut varieties [ ] 2 Fertilizer application [ ] 3.Weedicides and pesticides application [ ] 4 Storage practices [ ] 5. Marketing activities. [ ] 6.Others, please specify …………
6. During the 2023/2024 cropping season, did you have liquidity constraints in financing production (inputs)? 0 No [ ] 1 Yes [ ]
7. If yes, did you apply/ask for any loan to finance production? 0 No [ ] 1 Yes [ ]
8. If yes, which type of credit did you apply for? Formal Credit [ ] Informal credit [ ]
9. If yes, were you granted? 0 No [ ] 1 Yes [ ]
10. If yes, how much were you granted? Formal Credit GHc …… Informal credit GHc …
11. For what purpose, do you use the credit for? Purchase of farm inputs such as seeds [ ] fertilizer and renting of tractor [ ] For food for household consumption [ ] Others [ ]
12. What is the distance to a bank or a formal credit institution? …………………
13. Do you have access to agricultural extension services? 0 No [ ] 1 Yes [ ]
14. What is the distance to the nearest extension office? ………………..
15. What is the distance to the district capital? …………………………
16. Do you receive remittances from friends/relatives? 0 No [ ] 1 Yes [ ]
17. If yes how much do you receive as remittance? ……………..

18. Do you receive support from NGOs for your production purpose? 0 No [ ] 1 Yes [ ]
19. Do you have input dealers in your community? 0 No [ ] 1 Yes [ ]
20. What is the distance to the nearest input dealer? ……………………..
21. Do you have access to market for your produce 0 No [ ] 1 Yes [ ]?
22. If yes what is the distance to the nearest market? ………………………..

Part C: Farmland holding, tenancy and characteristics

1. What is your perception of the annual rainfall pattern in your farm locality? 0 Low[ ] 1 Medium [ ] 2 High [ ]
2. What is your total available arable land for all groundnut? …………………… .acres
3. What is your total arable land under current cultivation? ………………………… acres
4. Does water log on your groundnut plot? 0 No [ ] Yes [ ]
5. Did you benefit from any input assistance for fertilizer access in 2023/24 season? 0 No [ ] 1 Yes [ ]
6. What was the actual land under groundnut cultivation during 2023/24 season? ………………………………. Acres
7. How far is the distance of your groundnut plot from the house (Km)? ………………
8. How long have you been farming this groundnut land? ……………………………
9. How do you describe the organic matter content of the groundnut? (1=good 2=medium, 3= poor)

Part D: Biochar adoption among groundnut farmers

1. Are you aware of biochar? No [ ] Yes [ ]
2. How did you hear about biochar? MoFA [ ] MEDA [ ] Radio/TV [ ] Others [ ]
3. Do you have access to market information on biochar? No [ ] Yes [ ]
4. Have you received training/education on biochar production and utilization? No [ ] Yes [ ]
5. Do you belong to a biochar production group? No [ ] Yes [ ]
6. Did you participate in biochar production? No [ ] Yes [ ]
7. Did you or the group receive money for the biochar you produced? No [ ] Yes [ ]
8. How much did you receive?...................
9. Is there any biochar utilization support programme in your community? No [ ] Yes [ ]
10. Is there any biochar demonstration field in this community now or in the past? No [ ] Yes [ ]
11. Have you used biochar fertilizer in the 2023/24 production season? No [ ] Yes [ ]
12. Is biochar fertilizer available in the market for purchase? No [ ] Yes [ ]
13. What is the distance to the nearest biochar fertilizer source in your community? ………

14. What is the quantity of biochar fertilizer (kg) did you applied on your farm last season (2023/24) ………………?
15. What is the cost per kg of biochar fertilizer in GHS…………..?
16. Farmers motive for using biochar

Motives of biochar use	Strongly agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly disagree (5)
Improve soil structure					
Cost saving					
Lack of enabling policies					
Increase crop yield					
Increase drought resistance					
Improve food security					
Mitigate climate change					
Reduce soil acidity					
Reduce need for fertilizer					

17. **Challenges of accessing biochar**

Challenges	Strongly agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly disagree (5)
Insufficient access to experts and knowledge					
Lack of awareness of biochar					
Lack of enabling policies					
Limited access to capital					
Alternative use of the feedstock					
Interfere with tradition and customs					

Section B: Production Characteristics

Part A: Variable Input Cost:

Crop	**DI1**	**DI2**	**DI3**	**DI4**	**DI5**	**DI6**	**DI7**	**DI8**
	What quantity of [crop] seeds did you use on farm?	What type or variety of the seed did you plant on farm? [ ] improved seed [ ] local seed	If any seeds were purchased, what quantity was purchased? (kg)	How much did you pay for the purchased seeds used on farm? (GH)	Did you apply fertiliser? [ ] No [ ] Yes	Which type did you apply? **Codes** 1 Yara legume fertiliser 2 TSP fertilizer 3 organic fertilizers 4 OFA fertilizer **5 Biochar** fertilizer	What quantity was applied? (Kg)	What was the unit price? (GHc)
Groundnut								
soybean								
Others								

Crops	**DI9**			**DI13**		
	Did you apply pesticides? 0=No 1=Yes			Did you apply weedicides? 0=No 1=Yes		
	DI10	**DI11**	**DI12**	**DI14**	**DI15**	**DI16**
	Quantity applied on farm (litres/kg)	Unit Price (GH₵)	Total expenditure on pesticides GH₵	Quantity applied on farm (litres/kg)	Unit Price (GH₵)	Total expenditure on weedicides GH₵

Groundnut						
Soybean						
Others:						

DI17. What is the distance to input (fertilizer, pesticides, weedicides, improved seeds) market? …………………………………… Km.

DI18. What is the means of transport to the market? 1 = Walking 0= Otherwise

DI19. What is the nature of the road infrastructure from the community to the market? (1=good 2=medium, 3= poor)

DI20. Which of the following technologies did you employ on your groundnut farm? *Tick the ones that apply.*

[ ] Mulching
[ ] Minimum/zero tillage
[ ] Improved seed varieties
[ ] Organic fertilizer
[ ] Irrigation
[ ] Cover cropping
[ ] Integrated Pest Management (IPM)
[ ] Construction of bunds
[ ] Crop rotation

Part B: Labour Input cost

Crop	DII1						DII2						DII3			
	Family						Hired						Communal			
							Did you use hired labour? 0=No 1=Yes						Did you see communal labour? 0=No 1=Yes			
	Males		Females		Children		Males			Females			Males		Females	
	Num.	Days	Num.	Days	Num.	Days	Num.	Days	Rate (GHc)	Num.	Days		Num.	Days	Num.	Days
Groundnut																
Soybean																
Others																

(***Please note, the labour activities include land preparation, sowing/planting, fertilizer and chemical application, weeding, harvesting and other costs***)

. Which operation do you use the labour for? (1=all farm operations, 2=land preparation, 3=planting, 4= weeding, 5=fertilizer application, 6=spraying, 7= harvesting, 8=others (specify) ………………………… **(Multiple responses allowed)**

Part C: Harvest, Storage and marketing

Crop	**DII1**	**DII2**	**DII3**	**DII4**
	What quantity of crop was harvested from plot over the 2023/24 farming season?	Was any crop lost during harvesting on field? 0=No 1=Yes	How much of crop did you lose in total? (%)	Do you treat harvest under storage with chemicals? 0=No1=Yes
Groundnut				

Soybean				
Others:				

Crop	**DII5**	**DII6**	**DII7**
	Did you sell crop? 0=No 1=Yes	Quantity sold during and since harvest in 2023/24	What unit price did you sell most of crop?
Groundnut			
soybean			
Others			

Part D: Livestock and other assets: Please, I will like to ask about your livestock and other assets of the household.

1.	Do you own any of these animals in the household?	**Cattle**	**Sheep**	**Goat**	**Pigs**	**Poultry**	**Others**
		0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes
2.	If yes, how many does the household own?						
3.	How many did you sell in 2023/24 season?						
4.	At what price did you sell most of this? GHc						
5.	How many did you buy in the 2023/24 season? GHc						
6.	Do you seek for vetenary services for them? 0=No 1=Yes						
7.	If yes, how much did it cost you to vaccinate them in the last 12 months? GHc						

Part F: Capital/Fixed Cost Estimation:

S/N	**Asset/Item**	**Do you have item?** **0=No** **1=Yes**	**If yes, how many?**	**How much did you purchase the most recent one? GHc**	**Price if you were to sell it now? GHc**
1	Cutlass				
2	Hoe				
3	Knapsack				
4	Irrigation pump				
5	Mobile phone				
6	Radio				
7	Television				

8	Bicycle				
9	Motorcycle				
1	Car/Moto-King				
1	Bullock/Donkey				
1	Thresher				
1	Tractor				
1	House				
1	Others, (specify)				

Section C: Household income and expenditure

Part A: Source of household income

S/N	**Source of income**	**Amount (GHC)**
1	Annual income from sales of farm output	
2	Annual income from sales of livestock	
3	Annual income from non-farm activities (provision of labour service on other farms)	
4	Annual income from non-agricultural activities e.g., teaching, carpentry etc.	
5	Gifts and remittances	
6	Aid (from NGOs/Gov't)	
7	Others specify …………	

Part B: Household Consumption Expenditure

Expenditure item		Amount per week (GHC)
1. Own-produced food: Estimate cost of own produced food (assuming you are to buy in your local market) per week.		
2. Purchased-Food: Estimate cost of food items (e.g., milk, meat, fish, oil, fruits, vegetables, salt, etc.) that you bought for the household per week.		
3. Food as gift: Estimate cost of food giving to you as gift by relatives and friends (assuming you are to buy them) per week		
Non-food consumption expenditure		**Amount per month (GHC)**
4. Accommodation (Assume how much you will pay if you are in your own house/room; maintenance cost should be included)		
5. Clothing		
6. School fee		
7. School books		
8. School feeding fee		
9. School uniform, sandals etc.		
10. Health or medication		
11. Transportation		
12. Utility;	(a) Water	
	(b) Electricity	
	(c) Kerosene	
13. Communication (telephone, postal etc.)		
14. Sanitation		
15. Ceremonies;	(a) Funerals	
	(b) Naming and outdooring ceremonies	
	(c) Parties/entertainments	

	(d) Tithes and offerings	
	(e) Gifts	
	(f) Others………………………	
16. Fuel/ Firewood		
17. Saving		
18. Loans		
19. House rent		
20. Purchase of cars		
21. Purchase of bicycle, motor bike		
22. Maintenance of assets (e.g. TV, Motto bikes, Cars etc)		
23. Others…………………………………………….		

Hubeida Abdulai

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AI detection includes the possibility of false positives. Although some text in this submission is likely AI generated, scores below the 20% threshold are not surfaced because they have a higher likelihood of false positives.

Caution: Review required.

It is essential to understand the limitations of AI detection before making decisions about a student's work. We encourage you to learn more about Turnitin's AI detection capabilities before using the tool.

Disclaimer

Our AI writing assessment is designed to help educators identify text that might be prepared by a generative AI tool. Our AI writing assessment may not always be accurate (i.e., our AI models nay produce either false positive results or false negative results), so it should not be used as the sole basis for adverse actions against a student. It takes further scrutiny and human udgment in conjunction with an organization's application of its specific academic policies to determine whether any academic misconduct has occurred.

30-03-2026

requently Asked Questions

low should I interpret Turnitin's AI writing percentage and false positives?

he percentage shown in the AI writing report is the amount of qualifying text within the submission that Turnitin's AI writing etection model determines was either likely AI-generated text from a large-language model or likely AI-generated text that was kely revised using an AI paraphrase tool or word spinner.

alse positives (incorrectly flagging human-written text as AI-generated) are a possibility in AI models.

I detection scores under 20%, which we do not surface in new reports, have a higher likelihood of false positives. To reduce the elihood of misinterpretation, no score or highlights are attributed and are indicated with an asterisk in the report (*%).

ne AI writing percentage should not be the sole basis to determine whether misconduct has occurred. The reviewer/instructor ould use the percentage as a means to start a formative conversation with their student and/or use it to examine the submitted signment in accordance with their school's policies.

hat does 'qualifying text' mean?

ur model only processes qualifying text in the form of long-form writing. Long-form writing means individual sentences contained in paragraphs that make up a nger piece of written work, such as an essay, a dissertation, or an article, etc. Qualifying text that has been determined to be likely AI-generated will be ghlighted in cyan in the submission, and likely AI-generated and then likely AI-paraphrased will be highlighted purple.

n-qualifying text, such as bullet points, annotated bibliographies, etc., will not be processed and can create disparity between the submission highlights and the rcentage shown.