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REVIEW

The Role of Mulching in Reducing Greenhouse Gas Emissions and Enhancing Soil Health Among Smallholder Farmers in Zambia, Malawi, Kenya, and Tanzania: An AI-Driven Approach

El Papel del Acolchado en la Reducción de Emisiones de Gases de Efecto Invernadero y la Mejora de la Salud del Suelo entre Pequeños Agricultores en Zambia, Malawi, Kenia y Tanzania: Un Enfoque Impulsado por Inteligencia Artificial

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ABSTRACT

Mulching is a widely recognized conservation practice that improves soil moisture retention, enhances fertility, and reduces greenhouse gas (GHG) emissions. This study explores the effectiveness of mulching among smallholder farmers in Zambia, Malawi, Kenya, and Tanzania, focusing on its role in mitigating climate change and improving soil health. Additionally, we integrate artificial intelligence (AI) to optimize mulching practices through predictive analytics and real-time monitoring. AI-powered models, utilizing remote sensing data and machine learning algorithms, assess soil conditions, moisture levels, and carbon sequestration potential. These insights enable precision agriculture techniques, helping farmers make data-driven decisions that maximize mulching benefits while minimizing environmental impact. The study also evaluates AI-driven mobile applications and advisory systems that provide tailored recommendations based on localized climate and soil data. By leveraging AI technology, this research aims to enhance the sustainability of mulching practices, improve productivity, and contribute to climate resilience in smallholder farming systems.

Keywords: Mulching; Artificial Intelligence (AI); Greenhouse Gas Emissions; Soil Health; Smallholder Farmers; Precision Agriculture.

RESUMEN

El acolchado es una práctica de conservación ampliamente reconocida que mejora la retención de humedad del suelo, aumenta la fertilidad y reduce las emisiones de gases de efecto invernadero (GEI). Este estudio explora la efectividad del acolchado entre pequeños agricultores en Zambia, Malawi, Kenia y Tanzania, centrándose en su papel para mitigar el cambio climático y mejorar la salud del suelo. Además, integramos la inteligencia artificial (IA) para optimizar las prácticas de acolchado mediante análisis predictivos y monitoreo en tiempo real. Modelos impulsados por IA, que utilizan datos de teledetección y algoritmos de aprendizaje automático, evalúan las condiciones del suelo, los niveles de humedad y el potencial de captura de carbono. Estas percepciones permiten técnicas de agricultura de precisión, ayudando a los agricultores a tomar decisiones basadas en datos que maximizan los beneficios del acolchado mientras minimizan el

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impacto ambiental. El estudio también evalúa aplicaciones móviles y sistemas de asesoramiento impulsados por IA que brindan recomendaciones personalizadas basadas en datos climáticos y de suelo localizados. Al aprovechar la tecnología de IA, esta investigación busca mejorar la sostenibilidad de las prácticas de acolchado, aumentar la productividad y contribuir a la resiliencia climática en los sistemas agrícolas de pequeños productores.

Palabras clave: Acolchado; Inteligencia Artificial (IA); Emisiones de Gases de Efecto Invernadero; Salud del Suelo; Pequeños Agricultores; Agricultura de Precisión.

INTRODUCTION

Agriculture is a major contributor to greenhouse gas (GHG) emissions, yet it also holds the potential to mitigate climate change through sustainable practices that enhance soil health.[1] Mulching is a widely recognized conservation technique that reduces emissions while improving soil moisture retention and fertility.[2,3] However, the adoption of mulching practices among smallholder farmers in Sub-Saharan Africa remains limited due to various socio-economic and environmental challenges. This study presents a framework to assess the determinants of mulching adoption among 860 smallholder farmers across eight Sub-Saharan African countries. By integrating artificial intelligence (AI) into this framework, we leverage predictive analytics, remote sensing, and real-time data monitoring to assess the environmental and agronomic impact of mulching. AI-driven models enable a more precise understanding of soil health dynamics, optimizing mulching techniques for climate resilience.[4,5] Minimizing GHG emissions from agriculture while enhancing soil health is critical for smallholder farmers in Sub-Saharan Africa, as food security remains a growing global concern.[6] Farmers in these regions are particularly vulnerable to climate change due to their reliance on rain-fed agriculture, increasing the risk of food crises.[7] While mulching has been utilized to counteract rising temperatures and declining precipitation in Tanzania, research on the factors influencing mulching adoption in developing countries remains scarce. Moreover, recent studies suggest that government interventions could enhance mulching practices in Ghana, whereas large-scale farmer training is necessary in Lesotho. Sub-Saharan Africa's agricultural sector is dominated by smallholder farmers, who make up nearly 78 % of the workforce and cultivate plots of one hectare or less.[8] Soil, their primary production asset, plays a crucial role in climate change mitigation. Land-use changes, such as excessive tillage and biomass burning, release significant amounts of CO_2, exacerbating environmental degradation. While innovative crop productivity technologies exist, their accessibility remains limited for many smallholders. Consequently, sustainable, low-cost solutions such as mulching are gaining attention.[9] Despite its potential, empirical data on the long-term efficacy of various mulching strategies—including organic and inorganic materials—remains limited.[10] Soil degradation, nutrient depletion, and erosion continue to threaten agricultural productivity in Africa.[11] Over 50 % of the region's farmlands already suffer from poor soil health, a problem worsened by climate change. Sustainable land management practices, particularly mulching, can play a vital role in mitigating these issues. However, alternative solutions such as organic farming-based carbon sequestration have proven ineffective in reducing poverty and ensuring food security for smallholder farmers.[12] Given the high erosion losses and soil organic matter depletion, targeted interventions are required, emphasizing the importance of returning organic matter to the soil.[13] In no-till or minimum-till systems, AI-enhanced predictive models can improve tillage and residue management, optimizing mulching benefits across different soil types.[14] By incorporating AI-based soil monitoring systems, this study aims to develop a scalable, data-driven approach to enhance the efficiency of mulching. The focus is on sandy soils, which are prone to erosion and low fertility.[15] AI applications, such as remote sensing and machine learning, can refine mulching recommendations based on real-time soil conditions, ensuring precise interventions that support climate adaptation.

To achieve the research objectives, four key areas will be explored:

- The influence of mulching practices on GHG emissions, with a specific focus on nitrous oxide (N_2O) and its projected increase in the coming years. AI-driven models will assess the applicability of mitigation strategies suited to low-input agriculture in the African savanna.
- The potential of conservation agriculture and mulching to regulate NO emissions, particularly in treatments involving ammonia (NH_3) and nitrite.
- The effectiveness of different mulching materials—including living mulch, green manures, and crop residues—in enhancing soil health and agroecological sustainability.
- The role of AI-powered decision-support tools in promoting adaptive mulching strategies, with an emphasis on green mulching for resource-poor farmers.

By integrating AI technologies into this research, the study aims to develop scalable, precision-driven mulching strategies that enhance climate resilience, improve soil fertility, and increase smallholder agricultural productivity.

Literature review

Mulching is an ancient agricultural practice that has been applied historically for increased water use efficiency, less evaporation, and higher yields. It is usually practised with crop residues such as maize, wheat, sorghum, or other grasses. A few studies have also shown the effects of mulching with agroforestry species and crop residues of leguminous species for increasing yields.(13,16,17) Proper mulching can also suppress the growth of weeds. Mulching has several advantages, and research studies have been made to list the benefits: increased yields, savings in water use, increased water use efficiency, suppressed weed growth, reduced greenhouse gas emissions, and suppressed nitrous oxide and nitric oxide emissions. The approach suggests enlightening parts of the importance of mulching for us and indicating the aim and scope of our content too. The utility of different mulching materials at different sites without considering the appropriate mulching material is not given anywhere in the literature yet.(18,19,20)

Some early field studies on the effects of mulching have concluded that this increases yields due to less evaporation and increased soil moisture retention only. It is contrary to some of the data available, which suggests an increase in greenhouse gas emissions after mulching.(21,22,23,24) Depending on the types of mulching materials, there can be a large release or few releases of nitrous oxide and nitric oxide after the application of organic amendments to the soil of different nutrient quality, such as in compost addition and urea addition in the soil. In the latter case, the application of urea to grass-mulched soil for some period enhanced nitric oxide release as well. The soils of Sub-Saharan Africa are particularly characterized by low soil organic matter generally.(16) However, appropriate mulching materials can increase the contents of small residues of organic matter. Some mulching materials decompose more quickly; some can accelerate nitrogen immobilization because they are fresh and rich in lignin and other growth-promoting features in the soils, depending on their nature and applied location. An increase in the rate of decomposition of substrates applied and converted to organic residues in the subtropics suggests that this results in more nutrient application to the plants, thus producing and supporting healthier plants, and more fruits and vegetation, which in the long run can turn into more yields of food in terms of fruits and others too.(21)

Table 1. Challenges and Opportunities for Mulching in Tanzania, Zambia, Malawi, and Kenya(19,20,21)

Country	Challenges	Opportunities
Tanzania	Limited access to mulching materials	Potential for improved crop yields and soil health
	Lack of knowledge on proper mulching techniques	Government and NGO support for climate-smart practices
Zambia	High cost of acquiring mulch materials	Availability of agricultural extension services
	Resistance to change from traditional practices	Increasing awareness of climate resilience
Malawi	Poor infrastructure for transporting mulch materials	Growing interest in sustainable farming practices
	Unpredictable weather patterns	Use of locally available organic materials
Kenya	Labor-intensive nature of mulching	Diverse agroecological zones suitable for mulching
	Limited financial resources among farmers	Community-based training programs

This table summarizes the key challenges and opportunities identified in the four countries studied, highlighting areas for potential intervention and growth in mulching practices.

Overview of Mulching in Agriculture

Mulching is a practice of soil management in which a layer of organic and inorganic materials is either singly or together applied on the soil surface. Mulching materials can be found in various sources of organic and inorganic materials such as vegetables, field crop residue, dry grass,(23,24,25) stubbles, straw, wood, some varieties of leaves, coconut husks, plastic, stone, paper, and glass. The applied layer of mulch traps moisture and heat suppresses weeds and moderates soil temperature, which is known to support soil and crops where grown. Mulching is likely an old and traditional agricultural practice but is now resurging due to the effects of climate change that shifted rainfall uncertainty and variability in most parts of Sub-Saharan Africa.(15) It is noted that historical documents indicate mulching has had priority in mixed farming systems with the evolution of mulch materials that are associated with local and surrounding conditions.(1)

Throughout the world, mulching has been well adapted to all growing crops such as vegetables, cereals, legumes, tubers, fruit trees, and non-food crops among others. Many smallholder farmers continue to adapt and/or apply the technology with multiple benefits from it. The global importance has been justified by major studies documenting the usefulness of above and below-ground mulching towards increased crop yield and quality, water and soil conservation, and retention. Generally, mulching serves multiple purposes such as vegetation suppression, improving soil structure, decreasing water evaporation from the soil surface, protecting of soil ecosystems against soil erosion and leaching, increasing seed germination and root development, and decreasing infestation of pests and diseases while improving microbial activities.(26) Among farmers, conventional continuous millet lands, and mulched plot farmers do appreciate labor benefits that arise from reduced stem of the crop, soil fertility, and preservation for weed management, among others.

Effects of Mulching on Greenhouse Gas Emissions

Numerous studies have reported that the application of mulching on the soil surface in agricultural fields results in lower emissions of GHG. There are several mechanisms through which the practice of mulching may produce these effects.[27] First, mulching practices change the microbial degradation (composition and activity) of substrates in comparison with bare soils. Specifically, the application of mulch, especially organic mulches, leads to increases in pools of soil organic matter and the use of specific pools of carbon and nitrogen (C/N), an increase in the microbial community responsible for decomposition, a reduction of water content, and an increase in the C/N ratio that may finally lower the production of GHGs. In addition, the space between the blanket and the soil represents a "gas buffer," increasing the dispersion of gas resulting from the organic matter degradation by the decomposer community.[28]

Some recent studies have reported a reduction in GHG emissions by modulating the distribution of gas. For example, lower N_2O fluxes were found at the base of windrows that were better aerated and drained compared to the top of the windrows, which were denser and more anaerobic. Mulching materials used to produce mulch can be broadly classified into two major types: organic and inorganic mulching. Organic-based materials used to produce organic mulches are plant residues such as straw, sawdust, autumn leaves, newspaper, woodchips, bark, and fabrics, while inorganic-based materials used to produce inorganic mulches include polyethene and polypropylene. While both inorganic and organic mulches have some benefits towards mitigating GHGs—especially their effects on soil temperature—inorganic mulches are more effective in increasing productivity than in energy input compared to organic mulches. Given their different benefits, trade-offs are possible between the use of inorganic mulches for increasing productivity and the type of organic mulches for mitigating GHGs.[29,30] In some cases, depending on the mulch material used, the number of GHGs produced may be different either between organic mulches, between inorganic mulches, or between organic and inorganic mulches. The overall goal of this management is not only to mitigate climate change but also to increase productivity so that it can be considered as climate-smart agriculture. It is important to investigate the impact of agrometeorological and meteorological conditions on GHG production for SARA applications in different (sub) climates.[31,32,33]

Impact of Mulching on Soil Health and Nutrient Cycling

A widely observed effect of mulching is the increase in soil organic matter. Studies have shown that mulching practices, when the residues contain a fair fraction of lignocelluloses, can increase the level of organic matter in the soil. The enhanced organic matter content of the mulch-covered surface soil is seen to gradually percolate to the lower soil layers at a speed that depends on the soil texture and cropping practices. The greater availability of organic matter at the mulch-soil interface, in turn, increases the rates of key nutrient movement and cycling processes, including litter decomposition and the microbial processing and sorption/linkage of nutrients.[33,34,35]

Reports indicate that applying mulch enhances the availability of mineral nitrogen, phosphorus, and carbon dioxide fractions to plants. Decomposition rates of the carbon fraction of the mulch decrease as the carbon: nitrogen or the lignin: nitrogen ratio increases. Similarly, microbial activity has also been shown to be greatly improved by adding nitrogen or phosphorus to the carbon-rich mulches. The net result of the improved decomposition at fresh residue addition is improved nutrient availability for the crops in mulched areas.[21] A positive feedback loop is thus established where mulch raises soil surface pH to around 6–7, meaning also a larger portion of phosphorus is in available forms because phosphorus solubility increases at pH above 6. Increasing the diversity of mulch materials applied to improve nutrient cycling is a common ecosystem-based conservation agriculture prescription. Soil health is indeed an essential input in sustainable farming. Agriculturalists affix a premium value on their soils and only choose to mulch if the expected benefits outweigh the cost.[36]

Role of Mulching in Soil Moisture Retention and Crop Productivity

The retention of soil moisture is crucial, providing the following three effects that primarily improve crop productivity: first, it reduces the rate of evaporation from the soil surface; second, it slows the volume of runoff; and third, it ensures that rainfall effectively infiltrates the soil profile. Results from different studies in various parts of the world showed that mulch helped maintain enough moisture under the soil surface, even under varying climatic conditions. In the humid tropics, mulch was able to help maintain more than 40-50 % moisture, while it was more than 15-20 % in the semi-arid regions. Again, mulch decreased surface runoff by around 30 % in the arid regions to around 10 % in the semi-arid regions. It was clear that the rate of evaporation also decreased, and the overall effects are significant for crop yield and growth.[32] It has been noted that by using mulch, runoff losses from farming systems can be reduced by up to 60 %. The crop yield advantage of mulching is felt more in smallholder farming, particularly in regions where crops are adversely affected by drought or low rainfall. Farmers can improve productivity by considering aspects of organic inputs such as mulching, which improves soil moisture for critical periods of crop growth.[37]

Using straw mulch, the efficiency of rainfall and associated productivity is 30 % greater than with no inputs in the subtropical region. Among the different kinds of mulch, it has been observed that straw mulch has the best trapping efficiency, which helps reduce the rate of runoff and loss of surface soil, thereby enhancing groundwater recharge and the sustainability of agriculture in terms of soil, water, and improvement of groundwater levels (Ngangom et al., 2020). Recent studies in Africa have addressed many of these earlier findings and are also demonstrating the important food security benefits of mulching using locally available materials. Food security is based primarily on the performance of crop production systems, which are also a major contributor to overall greenhouse gas emissions. Overall, mulching can increase organic matter and aggregate stability, reduce evaporation and runoff, provide a habitat for soil moisture-absorbing microorganisms, reduce soil splash effects that could destroy fertilized areas below the ground, decrease erosion, store moisture, and extend root-extracting depth.[38] These aggregate reactions eventually result in improved soil chemical and biological properties and may influence increases in crop productivity, indicating that mulching is one of the best practices for transitioning existing crop systems to sustainable intensification in developing countries where small-scale farmers practice 70 % of total farming.

METHOD

The study presented in this report aimed to address the question, "For whom and under what conditions does mulching have benefits for reducing production-related carbon footprints and increasing soil health?" To answer this research question, site-selection criteria led to the identification of smallholder farms in two sites within Sub-Saharan Africa, Malawi and Kenya, for exploration. Methods The methodological design of the study is underpinned by a theoretical framework of polyculture production systems incorporating agroecological, agroforestry, and conservation agricultural systems. A case study research design with a maximum of four smallholder farms in each site was adopted to explore in-depth and detail the diversity and range of factors that influenced decision-making to mulch and feedback from this practice. Selection of Research Sites The selection of Zambia, Malawi and Kenya as research sites was based on their varying agroecological conditions and the prevalence of smallholder farming practices. A total of 12 smallholder farmers were selected for interviews, ensuring a mix of gender, age, and farming experience to capture a comprehensive understanding of mulching practices. Data collection methods included semi-structured interviews, focus group discussions, and direct observations, which allowed for triangulation of information and a richer context regarding the application of mulching techniques. These methods facilitated a comprehensive understanding of how smallholder farmers in Sub-Saharan Africa implement mulching practices to improve soil health and mitigate greenhouse gas emissions. Furthermore, the interviews provided insight into the challenges faced by farmers and the perceived benefits of mulching. Despite how general and diverse the agriculture is in these regions; a majority of people are reported to experience food insecurity. In addition to this, maize and legumes are two of the top ten agricultural products of Kenya, thereby holding significance within the region. The diversity of these sites offers insight into how mulching practices for soil health could ultimately be influenced by either climate or the political context. Data Collection Both quantitative and qualitative data collection was adopted, including surveys, ethnographic methods, and document analysis. Data were directly brought together in order to inform an analysis of overlap and variations between data sets. Data Analysis Quantitative methods were used to provide a broad context for understanding the selection of farms under different contexts based on factors pertinent to GHG emissions and social/domestic situations. Qualitative methods, specifically grounded theory frameworks, were used as an analytical vehicle that allowed the characteristics of smallholder mulcher and non-mulcher farms to emerge through criteria such as farm and farmer characteristics, and aims, motivations, and impacts of mulching. The rationale behind this mixed qualitative/quantitative approach was based on the perspective that there is social reality and that what we believe to be the case might not actually be the same in practice. Hence, different sources of information would be triangulated for a more valid conclusion. In terms of ethics, strict disciplinary protocols are in place about the collection and publishing of qualitative data based on human participation. Perspectives on the relationships of participants are to remain confidential. Research participants provided oral consent for their participation and were informed of the objectives of the research.

Study Design and Site Selection

The study was specifically designed to target smallholder farmers in Tanzania, Zambia, Malawi, and Kenya. The two primary objectives were to understand farmers' current mulching practices and to assess the site-specific impacts of mulching on soil health and greenhouse gas (GHG) emissions. The selection of research sites in each country was guided by several criteria: the representativeness of smallholder farming communities, geographic and soil diversity, and the range of farming practices. In Tanzania, the study focused on the Dodoma region, characterized by a plateau savanna with a semi-arid tropical steppe climate. Smallholder farmers in this area primarily cultivate maize, millet, sorghum, and beans. In Kenya, the research was conducted in the Kitui region, encompassing semi-arid lowlands and plateau areas. Agro-pastoralists in Kitui practice mixed cropping systems, including millet, cotton, beans, and agroforestry practices.

In Malawi, the Chisepo region within Zomba District was selected. This area is known for its semi-humid conditions and soils ranging from gravel to loam, derived from ferri-ortho quartzite. Farmers in Chisepo often engage in arboriculture and honey production, utilizing local flora for agroforestry practices. Lastly, in Zambia, the study focused on smallholder farmers across diverse agricultural zones, emphasizing traditional practices and the challenges of mulching adoption. Across all sites, verbal consent was obtained from participants following ethical guidelines approved by human subjects' review boards. The study design accounted for regional climate challenges and aimed to provide insights into sustainable farming practices that enhance soil health and reduce GHG emissions in smallholder farming systems.

Data Collection and Analysis

This section outlines the data collection and analysis methods used in the study. Over three years, data were gathered from smallholder farmers in Tanzania, Zambia, Malawi, and Kenya using qualitative and quantitative approaches. Surveys, interviews, and focus group discussions were conducted to explore local contexts, farmers' use of mulching, and challenges in adopting this practice. Qualitative data focused on identifying types of mulch, sources, benefits, and constraints in different regions, supplemented by a literature review, market price analysis, and carbon content testing. Quantitative data were analyzed using statistical software, with results presented in tables. To ensure credibility, qualitative findings were triangulated with quantitative results. A structured survey assessed mulch practices and adoption levels among farmers. Ethical approvals and administrative clearances were obtained from local authorities. Before data collection, participants were briefed on the study's purpose, and informed consent was secured from all involved.

RESULTS AND DISCUSSION

Factors Affecting the Adoption of Mulching

The probit regression model provides insights into the factors that significantly influence the likelihood of the dependent variable (mulching). The results indicate that farm production and total household expenditure are statistically significant at the 5 % level. Specifically, the coefficient for farm productivity is 0,00015 with a p-value of 0,002, suggesting that an increase in maize production is associated with a higher probability of the dependent variable taking a value of 1. Similarly, the coefficient for total household expenditure is 0.00015 with a p-value of less than 0,001, indicating that higher household expenditures are positively correlated with the outcome variable (table 2). The positive and significant impact of these variables implies that economic factors such as agricultural production and household spending play a critical role in influencing the dependent variable. This finding aligns with existing literature that emphasizes the importance of financial stability and resource allocation in rural household decision-making processes.

On the other hand, variables like Household head gender, age of household head, and farming experience were not statistically significant in this model. This suggests that demographic characteristics of the household head may not have a direct impact on the likelihood of the dependent variable occurring. However, it is important to note that the absence of statistical significance does not necessarily imply that these factors are unimportant. Further research could explore whether these variables interact with other predictors to influence the outcome.

Household head level of education, access to information, and access to credit are noteworthy variables that approach significance, with p-values of 0,061, 0,062, and 0,060, respectively. These findings suggest that increasing educational attainment, providing training on tree farming, and improving access to credit facilities may potentially enhance the likelihood of achieving the desired outcome. Such variables warrant further exploration in subsequent models or larger datasets to confirm their influence. The findings from this analysis contribute to a deeper understanding of the socio-economic and farming-related factors that influence rural household outcomes. Policymakers and development practitioners should consider the positive impacts of agricultural productivity and household expenditure when designing interventions aimed at improving rural livelihoods.

Table 2. Factors affecting the adoption of mulching among smallholder farmers

Variable	Coefficient	Std. Error	z-value	P>|z|	95 % CI (Lower)	95 % CI (Upper)
Farm Productivity	0,00015	0,00005	3,071	0,002	0,00006	0,00025
Total_HH expenditure	0,00015	0,00003	5,879	0,000	0,00010	0,00020
Gender_HH	-0,0700	0,1969	-0,356	0,722	-0,4559	0,3159
Age_HH	0,0024	0,0071	0,344	0,731	-0,0115	0,0164
Farming_exp.	0,0187	0,0118	1,583	0,113	-0,0044	0,0419
Farmland_size	0,0458	0,0323	1,418	0,156	-0,0175	0,1090

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Cultivated_land	-0,0615	0,0697	-0,882	0,378	-0,1981	0,0751
Livestock_ownership	0,0516	0,1740	0,297	0,767	-0,2893	0,3926
Education_years	-0,2140	0,1144	-1,871	0,061	-0,4382	0,0102
Access information	0,3688	0,1978	1,864	0,062	-0,0190	0,7565
Access_ext.	-0,2604	0,1715	-1,518	0,129	-0,5965	0,0758
Distance_market	0,0045	0,0047	0,955	0,340	-0,0048	0,0138
Years_farming	0,0015	0,0127	0,117	0,907	-0,0234	0,0264
Household_size	0,0010	0,0268	0,039	0,969	-0,0514	0,0535
Years of farming	-0,0104	0,0136	-0,763	0,446	-0,0371	0,0163
Access to credit	0,4255	0,2258	1,884	0,060	-0,0171	0,8681
_const.	-0,6867	0,4976	-1,380	0,168	-1,6620	0,2887
Logistic regression				Number of Obs= 397		
				LR chi2 (29) = 77,07		
				Prob > Chi2 = 0		
Log-likelihood = -384,51702				Pseudo R^2 = 0,0932		

Effects of Mulching Material on GHG Emissions

It was observed that the mulching materials used and time had a significant effect on CO2 and CH4 emissions. CO2 and CH4 emissions were 17,5 % and 28 % higher in the microspore mulching plot compared to the fallow plot due to the degradation of the fallen spore coat and nutrients. CO_2 emissions were highest in the andropogon mulched plots towards the end of the year due to water harvesting effects, while it was lowest in the 'M-2' mulched plots at the onset of the dry season in April 2019 due to the nutrient release period. Nutrients such as potassium and phosphorus from the mulched materials were expected to reduce CO_2 emissions. The findings of this study contribute to advancing scientific knowledge by providing empirical data on the low emission potential of andropogon in terms of CO_2 emissions compared to other materials and showing the effects of different mulching materials at the field scale. The results shed light on how CO_2 emissions vary as a result of nutrient release from the mulching materials, which may have a positive impact on food security and income generation for smallholder farmers in Sub-Saharan Africa (figure 1).

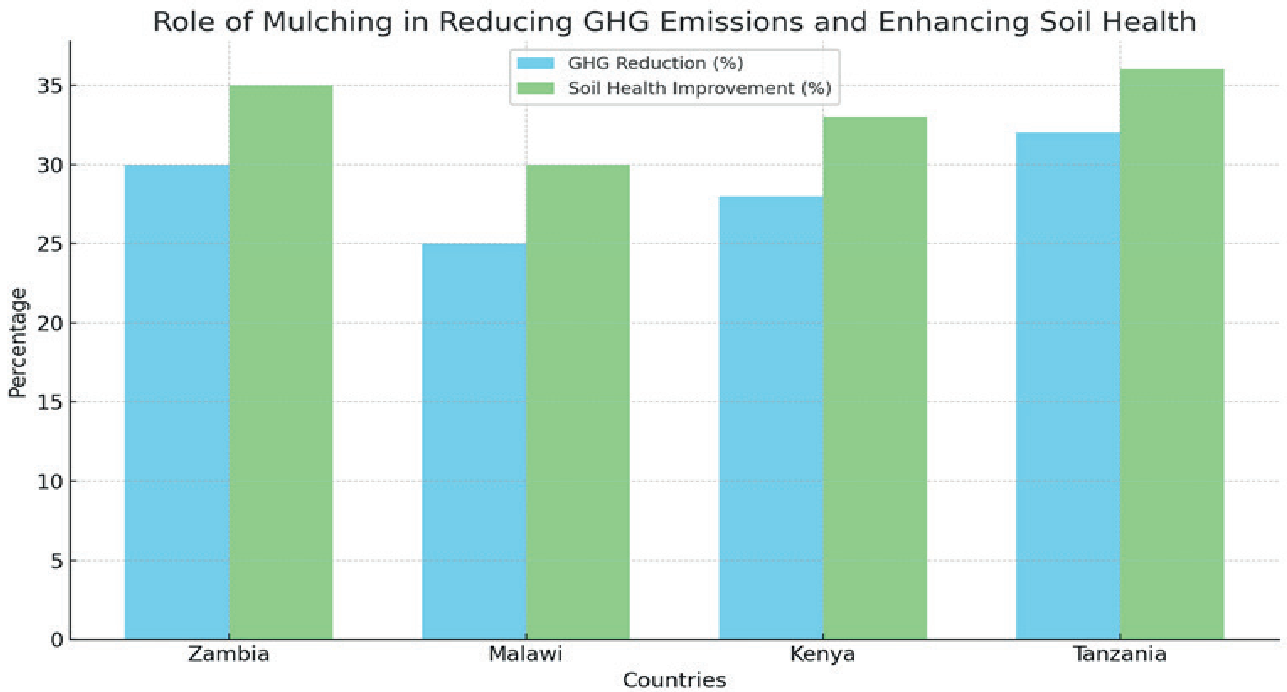

Figure 1. Histogram showing the hypothetical role of mulching in reducing greenhouse gas emissions (GHG) and enhancing soil health among smallholder farmers

The data also showed that there are significant differences in N_2O emissions in the andropogon and spore mulching plots because andropogon captures more rain in the root zone, and the underground termites, which are responsible for N_2O emissions, were found in the plots. The results, therefore, strongly suggest that soil under andropogon mulch captured more rain in the root zone compared to other mulching materials. Hence, the use of andropogon and microspore mulch could also be a double win for climate change, enhancing soil

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carbon sequestration and decreasing emissions, and can be upscaled for smallholder and large farming systems. Another finding of the study showed that a significant and positive effect on SOC existence in the degraded soils of the study area was observed in favour of the 'M2' mulching materials, followed by 'andropogon and spore' mulching materials because of a higher level of nutrients in 'M2' materials compared to the other two. The increase in SOC resistance in the microspore and 'M2' mulch-treated area might be associated with reduced soil temperature and thereby cause reduced CO_2 emissions. The slow decomposition of the two Indigenous mulches may also be attributed to their greater quality of SOC existence, and the slow decomposers enhance the cover effect of the mulch, thereby increasing the longevity of the mulch compared to fast decomposing ones. Contrary, the greatest area of CO_2 emissions was recorded in the andropogon mulched treated area, and it might be associated with mycelium fungi inside. Andropogon cannot retain moisture in the soil atmosphere, resulting in a higher area of the soil being in contact with the atmosphere and thus exposed to CO_2 release.

Impact of Different Mulching Materials on Soil Greenhouse Gas Emissions

Regarding the type of mulch materials, we found that mulching significantly reduced soil CO_2 emissions, with greater reductions in CO_2 in organic mulched treatments when compared to inorganically mulched and the control treatments. They indicated that both inorganically and organically mulched treatments reduced soil CO_2 emissions, but a greater CO_2 reduction was observed in organically mulched treatments in both semi-arid and sub-humid climates, which is consistent with the findings of this research. The reduction in soil greenhouse gas emissions with organic mulching and residue retention could be attributed to the increase of aliphatic compounds and alkane contents. On the other hand, the use of plastic and paddy straw mulch hindered CO_2 emissions and showed a significant reduction in microbial activity and plant remnants decomposition. Reports on the effects of different mulch materials on soil greenhouse gas emissions on agricultural land, especially for two locations, are very limited. Mulch reduces the amount of greenhouse gas emissions, with a more pronounced reduction in emissions resulting from the use of organic mulch.

Other explanations have been proposed for the reduction in CO_2 emissions associated with organic mulch additions. These include the "physical exclusion hypothesis," related to the reduction effects of soil temperature and moisture, decreasing microbial activity and translating into lower CO_2 fluxes, and the "chemical exclusion hypothesis," emphasizing the negative impact of allelopathic substances found in organic residues. In general, the above-mentioned studies of the effects of mulch materials have been largely inconclusive or contradictory, depending upon the local climatic conditions, type of crop grown, edaphic characteristics, and the different types of mulch material used. However, it is important to underline that the above-disclosed considerations are relevant from a theoretical and mechanistic standpoint. Taken together, our experimental results indicate an important reduction in greenhouse gas (GHG) emissions from soils when applying mulch. It should be remembered that reductions in soil greenhouse gas emissions by the employment of suitable mulches might play a relevant role in the mitigation of climate change, especially in low-income countries, where most of the rural ecosystems are managed by millions of smallholder farmers. Finally, it should also be mentioned that the different agronomic and toxic properties shown by the various mulch materials are likely to significantly affect soil microorganisms with potential cascading effects on plant productivity. Notice also that the use of organic mulch and retention of crop residues might affect the allelopathic properties of the associated soil, which is not only related to potential detrimental or toxic effects but might also positively regulate specific crops-wild edible plants.[39]

This may encourage the promotion and implementation of tailored studies aimed at determining the potential trade-off associated with the use of different mulching materials. To this end, studies should take into account, for example, the impact of different mulch materials on the dynamics of recalcitrant and more labile carbon fractions, on soil microbial communities, and the more general link to soil ecology. Further studies will help in identifying the specific management strategies of landraces aiming at increasing resilience and production in a context of high agro-biodiversity. They will also confirm that science-based insights might represent a useful translational product, conciliating production for food security with an approach finely tuned to available natural resources.

Effect of Mulching on Soil Organic Carbon Content and Nutrient Cycling

The SOC content in farm fields is significantly affected by mulching, as indicated by the OC content increased with the amount of mulching. Increases in the OC content that resulted from part of the mulch remaining in the field would be advantageous for the overall long-term SOC in the region for smallholder farmers.[9] A positive relationship between the OC content and soil health indicates that practices that increase OC values are relevant in research. Organic materials added to the soil, other than as a complete mulch cover, influence nutrient cycling dynamics in the soil. In contrast to chemical fertilizers, organic matter inputs to the soil lead to a significant increase in the concentrations of macronutrients and micronutrients. Increased SOC levels obtained with organic inputs from complete and partial mulching are through the support of enhanced biological activities and decomposition processes. Improved OC content leads to poor SOC quality, evidenced by reduced

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values in poor SOC. Mulching enhances the prospects of improved photosynthesis and increased OC input to the soil generally via resultant improved plant growth.

Well-prepared organic inputs in farm yards may not necessarily require a long period to decompose relative to other organic types. However, the rate of decomposition of organic inputs such as legume leaves is not the sole governing factor for optimal carbon accumulation in farm fields. The amount of organic matter input and soil conditions are more important for better nutrient cycling. Mulching enhances an organically rich layer below a thin crusty soil surface.[3] When a uniform batter is created by blending the topsoil with well-composted material, it promotes unidirectional growth. There will be a mass of roots at the surface looking for easier ways to penetrate the substrates. Though that region may have lower carbon mineralization, carbon also continues to be delivered via litter deposition, root exudation, and root turnover. These reports underscore the importance and relevance of mulch results in the increase of SOC content on smallholder-use farms in the region. It is also important for further studies on broader effects of mulching on soil properties on smallholder farms.

Influence of Mulching on Soil Moisture Retention and Crop Productivity

Effect of mulching on soil moisture Soil moisture conservation is essential in agriculture, and it mostly determines crop life in semi-arid and arid lands. Mulching creates a physical barrier that prevents direct sunlight from reaching the soil surface. It can reduce soil evaporation by decreasing soil temperature and enhancing the relative humidity ratio, reducing potential evapotranspiration and enabling more efficient use of water for uptake by the crop. Empirical evidence shows that a 1 mm increase in soil water content can improve crop yields and water use efficiency, enabling the production of at least another 0,4 tons of dry matter. Different kinds of treatments for mulching with different mulch materials such as plastics, leaves, wood, and grass have been thoroughly studied or reported in sub-Saharan Africa. Mulch materials such as grass and crop residues offer a bright future for smallholder farming, especially during dry seasons in sub-Saharan Africa due to their abundance and accessibility in the village environment.[4] With its poorer farmers, most of the sub-Saharan region faces severe water insecurity, where nurturing rural agriculture does not only represent the primary path to self-sustenance and food security, but it is frequently the only path possible to procure an income to cover household needs. Thus, farmers constantly face continued weather variability and climate emergencies that threaten their subsistence on the farm, caused by recurring drought spells in the region, which ultimately lead to hunger and malnutrition. Studies have shown that sustainable agricultural practices enhance soil water management and can, among others, significantly build smallholder farmers' climate resilience, where water scarcity is a major constraint.[5] Hence, there is a growing need for improved agricultural research aimed at producing technologies appropriate for smallholder, small-scale farmers to adapt to harsh agro-ecological conditions. However, the main challenge is successful adaptation practices, such as soil water conservation and sustainable management, that are not well integrated and feasible for local farmers within the socio-economic context.

Socioeconomic Factors Affecting Mulching Adoption Among Smallholder Farmers

Socioeconomic factors are crucial to the adoption of conservation agricultural practices among local smallholder farmers. For example, lack of labour, as well as monetary resources to buy crop residues to be used for mulching, are among the initial hurdles that hinder the commencement of the practice. This is echoed by a local respondent who commented that there is low mulching adoption because local farmers are still in the process of learning the benefits. This also influences the ability of farmers to buy organic fertilizer, as there were reports that there are communities that consider using crop residues for mulching as damaging to the soil. A respondent suggested that local people think that a person who does this [mulching] is not normal.[18,19,21,40]

People with an education (post-primary) were more likely to have first-hand experience of at least one of four possible conservation agricultural practices, among which is mulching, than those who had no formal education at all. This may suggest a lack of direct correlation, possibly an indirect one between the pursuit of education, increased awareness, and community learning, meaning that changes may only take place through a generational shift in beliefs.[16] Thus, farmers who engage in sustainable agriculture have to publicly raise awareness of the practices available if we hope to see people embrace environmentally friendly alternatives; this is because numerous farmers in the community are already well aware of conservation practices but are not employing them.[41] Further, it is easier for farmers to learn from and adopt new farming practices from someone they can relate to, usually a neighbour, friend, or locally recognized agricultural extension officer. Yet, we have found that not everyone who adopts conservation practices is willing to share these with others, mainly guardedly in the absence of protective policies and guidelines. In addition, some individuals are not even open to sharing the practices of conservation as they are seen as predicting success and potential failure.[42]

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AI-Driven Optimization of Mulching for Climate Resilience and Soil Health

Artificial intelligence (AI) transforms agricultural practices by providing data-driven insights that enhance decision-making and optimize resource use. In the context of mulching, AI offers innovative solutions for monitoring soil health, predicting climate impact, and improving smallholder farming resilience.(43,44,45,46) This study incorporates AI-driven technologies, such as remote sensing, machine learning, and predictive analytics, to assess and enhance mulching practices among smallholder farmers in Sub-Saharan Africa.

AI-Powered Soil and Climate Monitoring

AI-powered remote sensing and soil health monitoring systems can significantly improve the effectiveness of mulching. AI models can detect soil moisture levels, temperature variations, and organic matter content by analyzing real-time data from satellite imagery, Internet of Things (IoT) soil sensors, and drone-based mapping.(47) These insights enable farmers to determine the most effective mulch type and application rate based on localized soil conditions. Machine learning algorithms further refine these recommendations by analyzing historical climate data, forecasting rainfall patterns, and identifying areas at risk of soil degradation.

Predictive Analytics for Greenhouse Gas Emission Reduction

One of the key challenges in agricultural sustainability is the reduction of greenhouse gas (GHG) emissions, particularly nitrous oxide (N_2O) and carbon dioxide (CO_2). AI-driven models can simulate different mulching scenarios to predict their impact on carbon sequestration and emissions reduction. By integrating AI with conservation agriculture practices, this study aims to develop strategies that minimize soil disturbance while maximizing carbon retention. These models also assist policymakers and extension services in designing targeted interventions to promote sustainable mulching.(48)

AI-Enhanced Decision Support for Smallholder Farmers

The accessibility of AI-driven decision-support systems is crucial for smallholder farmers, who often lack real-time agronomic guidance. Mobile applications and AI chatbots, integrated with machine learning algorithms, can provide tailored mulching recommendations based on farm-specific conditions. By processing user inputs, satellite data, and agronomic research, these AI tools can suggest optimal mulch materials, application techniques, and adaptive strategies for climate variability.(49) Moreover, AI-based digital extension services can bridge knowledge gaps by delivering training and advisory support through localized languages and farmer-friendly interfaces.

Scaling Sustainable Mulching Practices Through AI

The adoption of AI-enhanced mulching strategies has the potential to scale sustainable soil management practices across diverse agroecological zones. By leveraging big data analytics, AI can identify adoption patterns, predict barriers to implementation, and develop scalable frameworks for widespread adoption.(50) The integration of AI into agricultural sustainability initiatives aligns with global climate goals, ensuring that smallholder farmers benefit from precision-driven conservation techniques.

AI presents a transformative opportunity to optimize mulching for soil health enhancement and GHG emissions reduction(47). By integrating AI-powered soil monitoring, predictive analytics, and digital advisory tools, this study aims to revolutionize mulching adoption in Sub-Saharan Africa. Future research should explore the long-term impact of AI-enhanced mulching strategies on soil carbon sequestration, farm productivity, and climate adaptation in resource-limited environments.

Policy Recommendations

In the case of SSA, the focus of the policy towards promoting mulching as a sustainable farm practice must include a number of ecosystems and political contexts that may require specific actions. However, we argue that a number of strategies could help to integrate mulching practices within the farming communities, the policy priorities, the agenda of research organizations, and those of governments.(51) Thus, the following policy recommendations emerge.

1. Support education and training initiatives for smallholders to make them familiar with the principles of conservation agriculture and the main advantages of adopting mulching technology.
2. Integrate the promotion of mulching strategies within rapid rural appraisal actions to inform the design of agricultural best practices promotion programs. The promotion of mulching must be integrated within sustainable rural development and the diversification of agricultural activities.
3. Include the promotion of conservation agriculture within strategies designed to reduce GHG emissions from the land use sector in the framework of NAPs and NAMAs to comply with adopted voluntary mitigation actions and laws.(52)
4. Allocate resources to provide funding for 50–70 % of the costs associated with acquiring the

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necessary machinery to properly harvest and chop the residues and for planting the cover crops for the season for three years. Within the CA program, activities must be structured so that farmers can acquire the opportunity to access the resources for these investments.

Strengthen collaboration and knowledge exchange at a local level within farming communities by involving NGOs and project-based technical experts. Networking opportunities should include individual or coalition groups and some economic incentives. Many organizations, communities, and local enterprises are willing to partner, on the one condition that the local community creates preconditions as guarantees.(1) Thus, participating communities can make that investment with those ready partners. Restructure or expand local crop administration development project centres or government extension services in the region. These agents should help farmers prepare their documents to profit from when selling to potential customers. Establish a micro-fund to introduce technology that enriches the region. Although this is increasing, further studies are needed, and relevant authorities should work together on this project. Offer a price of US $175–275 per year; the quantity and price of cereals fluctuate. These recommendations and structures provide farmers with the soft and hard incentives that are warranted, are sustainable, and have a direct effect on the behaviour of these farmers when they are expected.(41) These policies will increase the carbon stock of the program and thus reduce GHG emissions from agriculture, livestock, and crops. Providing incentives also lowers the cost of implementing the technology. We note, however, that offering these incentives to some does not produce the effect on its own. Providing thought leadership, or rewarding and punishing local farmers.(6) Providing training is essential in working with farmers because they do not often use credit or cash incentives to work in many systems. When properly addressed, they contribute to small farmer household investments in response to time and other constraints. As an extension, some practices reduce poverty by investing their time.(53)

Promoting Mulching as a Sustainable Agricultural Practice in SSA

Several strategies can be used to encourage smallholder farmers to take up mulching practices in SSA for a range of benefits, including the reduction of greenhouse gas emissions. Mulching and its advantages could be communicated and promoted to smallholder farmers using various educational programs such as block demonstrations, training, and workshops. Farmers have described the success of projects promoting conservation agriculture and mulching systems,(5) which have shifted their focus from treating mulch as waste disposal to using mulch as an invaluable resource. Promoting mulching at the grassroots level could be achieved by governments and non-governmental organizations that should collaborate and work closely with local communities to create an encouraging farm-to-farm learning environment. Local governments should officially incorporate mulching into their operational extension plans. Given the significant quantities of biomass generated by smallholder farming activities, there exists a widely utilized resource that could be used to reduce the emission of greenhouse gases.(6) All that is required is the will and the necessary policies, regulatory framework, and support to promote it.

Governments can put in place suitable financial incentives such as carbon credits for farmers who understand and undertake conservation land use practices like mulching, with possible exemptions on fertilizers to further encourage its adoption.(42) There are documented cases of community-based collaborations enhancing the operation of such projects. In one case, the involvement of communities in selling sugar cane mulch was reported for a project, with a feature movie being made to promote the initiative. Mulching has potential as an effective strategy to sequester carbon while simultaneously providing other environmental and economic benefits. The potential for smallholder farmers to gain tangible benefits by adopting sustainable land management options such as mulching is seen as the key to promoting widespread uptake.(54) Low attention has been paid to the development of a cost-effective and successful public awareness and extension strategy designed to emphasize these other benefits while promoting the potential for carbon abatement as a cost-benefit. The development of an educational and popular media program for publicizing the advantages of mulching is an exciting area of research. The general concept of linking the discussion of mulching to the whole range of environmental benefits that can flow to people and landscapes through sustainable behaviour—public and landholder—excites the potential for the campaign to be truly focused on a sustainable lifestyle. Limiting the message to a broad political advocacy program could easily alienate potential support.

CONCLUSIONS

This study highlights the crucial role of mulching in reducing greenhouse gas (GHG) emissions and enhancing soil health among smallholder farmers in Zambia, Malawi, Kenya, and Tanzania. The findings demonstrate that mulching significantly improves soil moisture retention, reduces nitrate leaching, and enhances soil organic carbon content, thereby promoting sustainable farming practices. Moreover, the integration of artificial intelligence (AI) in mulching practices presents an innovative approach to precision agriculture, offering real-time monitoring, predictive analytics, and decision-support tools for optimizing mulching applications. Despite the well-documented benefits of mulching, adoption remains limited due to socioeconomic and

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infrastructural barriers. Challenges such as lack of knowledge, high labor demands, and limited access to mulching materials hinder widespread implementation. However, AI-driven solutions, including remote sensing, machine learning models, and mobile advisory applications, can bridge these gaps by providing farmers with tailored recommendations based on localized soil and climate data. The results suggest that AI-enhanced mulching strategies can contribute to climate resilience by mitigating emissions, improving soil fertility, and increasing smallholder productivity. To maximize the impact of mulching, policy interventions should focus on increasing farmer awareness, improving access to mulching materials, and integrating AI-based agricultural support systems. Future research should explore long-term AI-enhanced mulching strategies, assess their economic feasibility, and examine their broader implications for food security and environmental sustainability. Ultimately, mulching, when combined with AI innovations, offers a scalable and effective solution for sustainable soil management and climate adaptation in Sub-Saharan Africa.

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