Original Research Article

Yield, Nutritional and Heavy Metal Bioaccumulation Responses of Cassava (*Manihot esculenta*) to Circular Economy-Based Innovations on a Mining-Degraded Landscape

Abstract

Mining operations in Ghana's Forest-Savannah Transition Zone have caused widespread land degradation, jeopardizing ecosystems, food security, and agroecological sustainability. In response, we conducted an experiment to evaluate the effects of biochar and poultry litter amendments on cassava (*Manihot esculenta*) growth, nutritional quality, and heavy metal accumulation at an illegal mining-degraded site in the Amansie Central District of Ashanti, Ghana.The experiment included five treatments: biochar (10 ton/ha), poultry manure (10 ton/ha), a biochar-poultry manure mix (1:1 ratio, 10 ton/ha each), and two control groups (degraded and forest sites). The combined biochar and poultry manure treatment yielded the highest cassava stover biomass, while nutritional characteristics of cassava tubers were influenced by treatment amendments. Additionally, biochar and poultry manure reduced the accumulation of Arsenic (As) and Lead (Pb) in cassava.This study showcases a circular economy-based approach that employs locally available resources to restore mining-degraded landscapes and enhance regenerative agricultural practices, reducing waste and emissions. Promoting the use of biochar and poultry manure amendments for ecological restoration in mining-degraded areas can contribute to sustainable land use, food security, and livelihoods. Policymakers should consider these strategies to align with global and national development goals while improving food systems and ecosystem services. Future research should explore the long-term impacts of cassava cultivation on amended mining sites and assess the potential of these amendments for agroecological enhancement and heavy metal immobilization.

Keywords: Biochar, Poultry Manure; Circular Economy, Cassava; Landscape Restoration

1. Introduction

Food security, safety, environmental sustainability are critical determinants of human wellbeing and a precondition for socioeconomic development. Since the expiration of Millennium Development Goals (MDGs) in 2015 and the transition to Agenda 2030, there has been numerous discussions around sustainability and circular economy with varying commitments from different countries towards achieving the Sustainable Development Goals (SDGs) generally and in particular the SDG 2 of ending hunger, achieving food security and improving nutrition(Surana *et al*., 2020). Eight years down the line, many countries across the world are still off track towards achieving this objective by 2030. Evidence from recent studies reveal that the world is progressing neither towards SDG target 2.1, of ensuring access to safe, nutritious and sufficient food for all people all year round, nor towards target 2.2, of eradicating all forms of malnutrition (FAO, IFAD, UNICEF, WFP, 2020). While effective food systems are a major pillar in global food security, agriculture productivity continues to be threatened by many environmental constraints triggered by climate change and human activities such as mining (Prăvălie *et al*., 2021). Africa's capacity to feed itself and become a major food supplier for the world continues to be challenged by unsustainable production patterns and increased need to produce healthier, safer and more nutritious food on less land with lesser chemicals and water, less waste generation and reduced greenhouse gases. To overcome this challenge, the need for a reversal from land degradation toward promoting ecosystem services, biodiversity and food safety cannot be overemphasized.

Remediation of degraded and contaminated mining landscape is paramount to ecological restoration for agricultural and forestry land uses and the sustenance of global food systems. According to Hindersah *et al.* (2018) about 25% of the total land has been degraded and 3.2 billion people have been affected by land degradation with severe impact on smallholder farmers who heavily depend on natural resources. Artisanal and small-scale gold mining (ASGM) is a significant contributor to land degradation and heavy metal contamination in Ghana impacting heavily on rural livelihood, agroecological activities and the risk of biomagnification. The study addresses the environmental problems caused by mining on agroecosystems. By using poultry manure and biochar as restoration amendments, the research seeks to mitigate the negative impacts of mining and improve the overall environmental quality of the degraded landscape (Adekiya *et al.* 2019). The use of abundant poultry manure and biochar demonstrates a circular economy-based approach. Both poultry manure and biochar are potentially underutilized resources with the potential to be recycled and repurposed, reducing waste and promoting regenerative agriculture practices (Gao *et al.* 2020). The study also acknowledges that the abundance of these amendment elements could also create environmental problems if not managed properly. Therefore, exploring their use for restoration purposes would be beneficial in tackling two challenges at once: land degradation caused by mining and the proper management of poultry manure and biochar to prevent potential environmental issues such as methane and black-carbon emission from decomposition and open biomass burning (Asante *et al.* 2019). The research specifically focuses on the Forest-Savannah Transitional Zone of Ghana, which is an ecologically sensitive area with high galamsey activities. By conducting the study in this ecological zone, the findings can be directly applied to this specific environment, ensuring the restoration measures are tailored to the landscape’s needs. The potential benefits of using poultry manure and biochar for ecosystem restoration have not been thoroughly explored in the Forest-Savannah Transitional Zone of Ghana. This study aims to fill this knowledge gap by investigating the impacts of these circular economy-based innovations on cassava yield, nutritional quality, and heavy metal bioaccumulation in the specific context of a mining-degraded landscape. Successful landscape restoration can have significant economic and social benefits for local communities, including increased agricultural productivity, improved food security, and enhanced livelihoods.

2 Materials and Methods

2.1 Study area and design

The study was conducted at AsikasuGalamsey site in the Amansie Central District of Ashanti (Fig.1) on a 5-year-oldgalamsey-degraded soil and a forest site as a control (400 meters from the galamsey-degraded experimental site) located in the forest-savanna transition zone of Ghana.

The ecological zone has a bimodal rainfall regime with annual precipitation between 1200 and 1400 mm. The soils at the experimental site were sampled from 5 different spots, bulked, sub-sampled and analyzed for chemical properties (Asante *et al.* 2019).

Figure 1. Map of study area.

A randomized complete block design with three replications was employed with each plot measuring 12 m^2 (3 m x 4 m). The plots received 10 ton/ha biochar, 10 ton/ha poultry manure, combination of 10 ton/ha biochar and 10 ton/poultry manure (1:1) two controls i.e. unamended degraded site and unamended forest site. Treatments were applied 4 weeks before planting to ensure adequate incorporation of treatment materials into rhizosphere environment. Cassava cuttings of the CRI-Abrabopa variety, obtained from the Crop Research Institute of the Council for Scientific and Industrial Research-Accra, Ghana, were planted using horizontal placement on small mounds. The CRI-Abrabopa variety, was chosen because it is well adapted to the Forest and Forest-Savannah Transition ecological zones of Ghana, resistant to Cassava Mosaic Virus Diseases (CMD) and developed for high yielding industrial starch that can be a better substitute to degradative mineral exploitation.

A spacing of1 m × 0.75 m was used, resulting in 16 plants per plot with 4 plants in a row for 4 rows. The fields were maintained by regular manual weeding with a hand-held hoe and inspection of any disease or pest attack. Five mature stems in the two middle rows were harvested manually after 12 months of growth (April 2019-March 2020 for first experiment and April 2020 to March 2021 for second experiment) to determine the yield. Data on number and weight of tubers per plant were collected. Yield data were taken on fresh tuber weight and stover weight. The above-ground biomass, made up of cassava stems cut at the soil surface(root-collar), leaves, and branches constituted the stover. Harvest Index (HI) was also determined as the ratio of the economic yield to the biological yield expressed as a percentage(Asante *et al.* 2019).

2.2 *Plant tissue analysis*

Using proximate analysis procedures as described in Bajpai and Punia (2015), the moisture, ash, protein, fat, carbohydrate and crude fibre contents of carrots were determined. Specifically, crude protein was determined by Kjeldahl Method(Eifediyi et al., 2010).

2.3 *Crude fat determination*

In an extraction thimble, 2 g of the dried material was weighed. A Soxhlet apparatus was used to house the thimble. A dry pre-weighed solvent flask was connected to the apparatus, and the needed amount of solvent (approximately 150-200ml of petroleum ether) was added, then the flask was connected to a condenser to extract for 2-3 hours. The thimble was removed after completion, and ether was reclaimed with the apparatus. The ether was removed using a boiling bath, then dried in a flask at 105°C for 30 minutes, cooled in a desiccator, and weighed(Boakye Peprah et al., 2020).

Calculation: The percentage of crude fat (% of DM) is determined from the relation;

$$Crude\ fat = \frac{Weight\ of\ fat}{Weight\ of\ Sample} x100$$

2.4 *Crude fibre determination*

A digestion flask was filled with 2 g of the dried, fat-free sample. The digestion flask was placed under the condenser and heated to boiling point in 1 minute with 200 mL of hot sulphuric acid. The sample was gently boiled for exactly 30 minutes. When foam became excessive, an antifoam was employed. The mixture was immediately filtered through linen and thoroughly rinsed in boiling water. The residue was re-added to the digestion flask, along with 200 mL of boiling sodium hydroxide solution. Within 1 minute, the new sample was placed beneath the condenser and brought to boiling point. The mixture was filtered through a porous crucible and rinsed with boiling water and around 15ml 95 percent alcohol after boiling for exactly 30 minutes. The sample was dried at 105°C until the weight was consistent, then cooled and weighed. The sample was ashed for 30 minutes at 550°C, cooled, and weighed. The weight of fiber was calculated using the difference method(Asante *et al.* 2019).

Calculation:

Crude fibre (% of fat-free DM)

$$= \frac{(Weight\ of\ crucible + dried\ residue) - (Weight\ of\ Crucible + ashed\ residue)}{Weight\ of\ sample}$$

2.5 *Ash determination*

A 2g sample was weighed into a dry, tared porcelain dish and placed in a muffle furnace for 4 hours at 550°C. After cooling in a desiccator, the sample was weighed(Shaw and Beadle, 1948).

Calculation:

The percentage of Ash (%) in the sample was determined by the relation below as

$$Ash(\%) = \frac{weight\ of\ ash}{weight\ of\ sample} x100\%$$

2.6 *Nitrogen-free extract (NFE)*

Nitrogen-Free Extract (NFE) was discovered by difference and represents non-structural carbohydrates like as starches and sugars. NFE was calculated using the formula below once the various components of the proximate analysis were determined(Shaw and Beadle, 1948):

$$\%NFE(on\ dry\ matter\ basis) = 100 - (\%CP + \%CF + \%Ash + \%EE)$$

Where, NFE = nitrogen free extract; EE = ether extract or crude lipid CP = crude protein; CF = crude fiber

2.7 *Carbohydrate determination*

Using the numbers obtained for NFE and crude fibre as reported in Asante *et al.* 2019 in the formula below, the % total carbohydrate was calculated(Pipatsitee *et al.*, 2019):

$$\%Carbohydrate = \%\ NFE + \%Fibre$$

2.8Heavy metal accumulation

The concentrations of heavy metals (Cd, Pb, As and Hg) were determined from atomic absorption spectrophotometer for the various metals at specified wavelengths (Osmani *et al.*, 2015).

Statistical analyses were done using a one-way analysis of variance (ANOVA) with version 11 of GenStats statistical package.

3 Results

3.1 Influence of biochar and poultry manure on cassava growth and yield characteristics

Stover yield responded significantly to biochar and poultry manure treatment during the first year of cultivation (Table 1). Combined biochar and poultry manure produced the highest stover yield (22.85 ton/ha) while forest topsoil control provided the least (14.24 ton/ha). Effect of treatments were, however not significant for root quantity per plant, root weight per plant, total yield and harvest index. During the second year of cultivation (Table 2), there were no significant treatment effect on growth and yield characteristics.

Table 1 Effect of Biochar and Poultry Manure on Cassava Growth and Yield Characteristics during 1st Year of Cultivation

Treatments	Root	Root	Tuber yield	Stover	HI

	qty/plat	Wt/Plt	(ton/ha)	Yield (ton/ha)	
10 ton/ha biochar	3.4	1.345	17.94	18.307c	49.44
10 ton/ha PM	3.5	1.521	20.28	21.81d	48.18
1:1 Biocher+PM @10 ton/ha	3.34	1.45	19.34	22.853e	45.65
Galamsey Soil control	2.97	1.436	19.15	17.298b	52.2
Forest topsoil control	3.4	1.345	17.94	14.241a	55.62
Mean	3.32	1.42	18.93	18.902	50.22
S.E.D	0.354	0.1593	2.124	0.0719	2.818
LSD0.05	0.817ns	0.3674ns	4.898ns	0.1659**	6.499

*S.E.D. Standard Error of the Differences of mean; *, ** Mean significant at 5 % and 1 % probability levels respectively*

Table 2 Influence of Biochar and Poultry Manure on Cassava Growth and Yield Characteristics during 2nd Year of Cultivation

Treatments	Root qty/plat	Root Wt/Plt	Tuber yield (ton/ha)	Shover yield (ton/ha)	HI
10 ton/ha biochar	3.12	1.29	16.73	15.61	51.71
10 ton/ha CM	3.21	1.396	17.22	18.06	48.77
1:1 Biocher+CM @10 ton/ha	3.06	1.33	16.7	19.26	46.69
Galamsey Soil control	3.03	1.217	18.41	18.08	50.46
Forest topsoil control	3.12	1.357	18.84	17.40	52.2
Mean	3.11	1.318	17.58	17.68	49.96
S.E.D	0.403	0.1279	1.463	2.21	3.128
LSD0.05	0.93ns	0.295ns	3.374ns	5.10ns	7.214ns

*S.E.D. Standard Error of the Differences of mean; *, ** Mean significant at 5 % and 1 % probability levels respectively*

3.2 Effect of biochar and poultry manure on cassava nutritional characteristics

During the first year of cultivation (Table 3), the effect of biochar and poultry manure on % carbohydrate, % protein and total ash was significant. % Crudefibre, % fat and % moisture were, however, not significant. Galamsey soil control gave the highest % carbohydrate (88.17) whereas forest topsoil control and the combined biochar-poultry manure gave the least (84.12 and 84.35 respectively). Galamsey topsoil control gave the least % total ash (7.95). Ten (10) ton/ha, combined biochar and poultry manure and forest topsoil control produced a comparatively high % total ash. During the second year of cultivation (Table 4), application of biochar and poultry manure had a significant effect on % carbohydrate and % protein. Galamsey soil control gave the highest % carbohydrate (87.76) and forest topsoil control gave the least (83.57). The combined biochar and poultry manure treatment produced the highest % protein (3.42). Galamsey soil control gave the least % protein (2.41). Percent (%) crude fibre, % fat, % moisture and % total ash were, however, not significant during the 2nd year of cultivation.

Table 3 Influence of Biochar and Poultry Manure on Cassava Nutritional Characteristics during 1st year of cultivation

Treatments	**% Carbohydrate**	**% Protein**	**% Crude Fibre**	**% Fat**	**% Moisture**	**% Total Ash**
10 ton/ha biochar	85.497b	2.19a	0.86	1.02	59.47	10.43a
10 ton/ha PM	86.395b	2.80c	0.89	0.98	60.15	8.94b
1:1 Biocher+PM @10 ton/ha	84.352a	3.32b	0.76	0.94	61.49	10.62a
Galamsey Soil control	88.175c	2.34a	0.66	0.88	61.65	7.95c
Forest topsoil control	84.124a	3.22b	0.81	0.92	63.8	10.93a
Mean	85.709	2.78	0.80	0.95	61.31	9.77
S.E.D	0.275	0.065	0.070	0.052	2.071	0.256
LSD0.05	0.633**	0.149**	0.161	0.121	4.775	0.590**

*S.E.D. Standard Error of the Differences of mean; *, ** Mean significant at 5 % and 1 % probability levels respectively*

Table 4 Influence of Biochar and Poultry Manure on Cassava Nutritional Characteristics during 2nd year of cultivation

Treatments	% Carbohydrate	% Protein	% Crude Fibre	% Fat	% Moisture	% Total Ash
10 ton/ha biochar	84.78ab	2.521ab	0.838	1.011	58.28	10.85
10 ton/ha PM	85.99ab	2.885bc	0.801	1.025	58.95	9.3
1:1 Biocher+PM @10 ton/ha	85.19ab	3.423d	0.739	0.991	60.26	9.66
Galamsey Soil control	87.76b	2.411a	0.639	0.923	60.41	8.26
Forest topsoil control	83.57a	3.321cd	0.785	0.962	62.52	11.36
Mean	85.46	2.912	0.76	0.982	60.08	9.89
S.E.D	0.797	0.1184	0.069	0.057	2.029	0.902
LSD0.05	1.838**	0.273**	0.159ns	0.131ns	4.679ns	2.079ns

*S.E.D. Standard Error of the Differences of mean; *, ** Mean significant at 5 % and 1 % probability levels respectively*

3.3 Effect of biochar and poultry manure on heavy metal accumulation

Biochar and poultry manure had a significant effect on cassava arsenic (As) and lead (Pb) accumulation. Cassava grown on unamended galamsey plots gave the highest As and Pb content during the first year of cultivation (Table 5). During the second year (Table 6), only As responded significantly to biochar and poultry manure treatments by reducing the amount accumulating in cassava. Unamended galamsey soil gave the highest As content in cassava. Mean As content for cassava grown on 10 ton/ha biochar plots and combined biochar-poultry manure plots were at par.

Table 5 Influence of Biochar and Poultry Manure on Heavy Metal Characteristics of Cassava during 1st Year of Cultivation

Treatments	**As**	**Cd**	**Hg**	**Pb**

	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
10 ton/ha biochar	1.783ab	1.15	3.12	2.47a
10 ton/ha PM	1.183ab	1.79	1.46	2.32a
1:1 Biocher+PM @10 ton/ha	0.843a	0.92	0.57	1.64a
Galamsey Soil control	2.06b	1.8	2.55	4.87b
Forest topsoil control	1.04ab	0.54	1.57	0.98a
Mean	1.382	1.24	1.85	2.46
S.E.D	0.3128	0.688	0.803	0.49
LSD0.05	0.7213*	1.586	1.852	1.129**

*S.E.D. Standard Error of the Differences of mean; *, ** Mean significant at 5 % and 1 % probability levels respectively*

Table 6 Influence of Biochar and Poultry Manure on Heavy Metal Characteristics of Cassava during 2nd Year of Cultivation

Treatments	**As (mg/kg)**	**Cd (mg/kg)**	**Hg (mg/kg)**	**Pb (mg/kg)**
10 ton/ha biochar	0.3856a	0.344	0.69	0.763
10 ton/ha CM	0.5451c	0.34	0.616	0.861
1:1 Biocher+CM @10 ton/ha	0.4015a	0.408	0.804	0.879
Unamended Galamsey Soil control	0.7058d	0.371	0.745	0.824
Forest floor top soil control	0.4498b	0.367	0.665	0.929
Mean	0.4976	0.366	0.704	0.851
S.E.D	0.0104	0.1253	0.22	0.2587
LSD0.05	0.02399**	0.289ns	0.5074ns	0.5966ns

*S.E.D. Standard Error of the Differences of mean; *, ** Mean significant at 5 % and 1 % probability levels respectively*

4. Discussions

4.1 Effect of biochar and poultry manure on cassava growth and yield characteristics

Plots receiving combined biochar and poultry manure produced the highest stover yield largely because of the improved cation exchange in the degraded soil. Whereas biochar widens the surface area for adsorption of nutrient elements, the poultry manure provides an increased concentration of both micro and macro nutrients resulting in improved nutrient uptake for the development of above-ground biomass. However, the improved stover yield did not translate into improved yield probably because of limited translocation of photosynthates from source organs to sink tissues of the root. While a study by Adekiya *et al.* (2019) observed that applying biochar and poultry manure increased maize biomass and yield, studies by Santo *et al.* (2021), Sierra-Gonzalez *et al.* (2021) and Li *et al.* (2020) show that increased stover yield may not necessarily translate into economic yield if there are rhizospheric stresses and imbalances in the micro and macro nutrients transport in the plant. In their work, Sarabi *et al.* (2019), found that photosynthesis down-regulation which restricts the assimilate translocation to sink tissues can result from a low water use efficiency, increased leaf abscisic acid (ABA) and flavonol contents from soil stressors, as well as increased osmotic potential in response to environmental stressors. Further, forest topsoil provided the least stover yield probably because of high soil sodium and clay content and microclimate which limited the photosynthetic capacity of cassava leaves for assimilate translocation into sink tissues. Sonti *et al.* (2021) argue that while urban forest patches can provide critical ecosystem services, regenerate native tree species and contribute significantly to environmental sustainability, there can be short term soil and microclimate-induced stresses which can affect the photosynthetic capacity and growth of succession plants and crops introduced to the forest environment.

4.2 Effect of biochar and poultry manure on cassava nutritional characteristics

The galamsey-degraded soil control gave the highest % carbohydrate probably because of insufficiency of partitioning of nitrogen and mineral-based assimilates into sink organs of the root. Consequently, the percentage of carbohydrate is expected to be elevated above other nutrients in the absence of adequate soil nutrients in the rhizosphere. In their work on maize response to environmental stresses, Gao *et al.* (2020) found that carbohydrate assimilate allocation was affected by environmental stresses shading and soil limitations. Similarly, in their work on carrot nutritional quality response Asante *et al.* (2019) explained that elevated % carbohydrate in root tubers may be due to enhanced release of stress hormones such as Gibberellins which induces the root tubers to take up more water in an attempt to obtain soil nutrients in order to compensate for insufficient nutrient arising from the reduction in nutrient transport. By extension of same arguments, % protein was highest for cassava grown on plots amended with the combined biochar and poultry manure. During the second year of cultivation, plots amended with combined biochar and poultry manure and forest topsoil control provided the highest protein content probably due to improved physicochemical characteristics of galamsey-degraded soil following amendments to the extent of being at par (Table 3) or slightly above those of forest topsoil (Table 4). While hunger, malnutrition and food insecurity continue to increase and worsen with the surge of COVID-19 across the globe, the need for governance actors to prioritize the improved management of agroecological landscapes with the right soil amendments to inform the right nutrient density in the plant for improved human nutrition and the prevention of morbidity and mortality due to non-communicable diseases is critical. The % total ash for 10 ton/ha biochar, combined biochar and poultry manure and forest topsoil were at par during the first year of cultivation possibly because of weather- and treatment-induced improvements in xylem-mediated transport of micro- and macro-elements resulting from enhanced physicochemical characteristics of the respective soils and the resultant improvements in assimilate translocation to the root tubers. The improved ash content consisting mainly of salty, inorganic constituents including metal salts are important for metabolic processes requiring ions such as Na^+, K^+, Ca^{2+} and other trace minerals which are needed for unique molecules such as chlorophyll (Wamalwa *et al.*, 2019) and hemoglobin (Awuchi *et al.*, 2020). Although the effect of soil amendment on the % total ash content during the second year was not significant, further investigation on sustained improvement of plant protein and ash content is required. This will enhance human and animal nutrition and food security particularly for cassava which is consumed by both humans and livestock.

4.3 Effect of biochar and poultry manure on heavy metal accumulation

Biochar and poultry manure reduced As content of cassava largely due to combined binding effect of biochar and poultry manure of As and the resultant immobilization effect that prevents As circulation in soil solution for cassava uptake. In their work, Scharfstein and Gaurf (2020), found that binding mode of flexible polypeptides of proteins and organic materials constitute an important factor in explaining the immobilization effect on a heavy metal like As in cassava. Kumar *et al*. (2020) and Mishra *et al*. (2019) also argue that because locally produced waste organic material can be used to make biochar and manure into low-cost adsorbents, they are particularly appealing for remediation and treatment systems. It is further argued that pyrolytic temperature is the most critical factor influencing biochar's sorption capacity, accompanied by pulverizing to increase surface area (Breda *et al.*, 2020). Additionally, in a study on the phytoavailability of heavy metals in plants Kwiatkowska-Malina (2018) found that organic amendments demonstrated significant sorption ability for a variety of pollutants, including heavy metals, which could result in their immobilization and, as a result, pollution protection for food and groundwater. Yang *et al.* (2018) in their sorption-desorption study investigating heavy metal responses found that incorporation of amended biochar and compost combinations into soil significantly promotes the sorption affinity of soil on metals. They argue that the sorption capacity of Cd and Zn was improved as the compost percentage rose in biochar-compost amendment due to the increase of organic matter and available phosphorus, while that of Cu was stronger with 10 and 20% biochar addition in biochar-compost combinations as a result of the formation of new specific adsorption sites.

5 Conclusion

The study demonstrates the potential of a circular economy-based approach to restore mining-degraded landscapes in Ghana's Forest-Savannah Transition Zone. By integrating biochar and poultry manure amendments into cassava cultivation, we not only achieved enhanced crop growth and improved nutritional quality but also effectively reduced the accumulation of toxic heavy metals, such as Arsenic and Lead, in cassava tubers. These findings offer a ray of hope for communities facing the dire consequences of illegal mining activities, including land degradation, disrupted ecosystems, and food insecurity.The success of this regenerative agricultural approach underscores its relevance as a sustainable solution with multiple benefits. By utilizing locally available resources, our approach minimizes waste and emissions while providing a tangible path toward ecological restoration. Moreover, it aligns with global and national development goals, including those related to sustainable agriculture, environmental conservation, and food security.Policymakers, local authorities, and environmental agencies should recognize the value of incorporating biochar and poultry manure amendments in land restoration initiatives, potentially scaling up these practices to address the broader issue of mining-related land degradation in Ghana and similar regions globally. As these strategies have proven to enhance land productivity and minimize the environmental footprint, they hold significant promise for mitigating the long-term impacts of mining activities.To further extend the applicability of this approach, future research needs to focus on long-term monitoring and assessments of amended mining sites, examining their potential for agroecological enhancement and heavy metal immobilization. Continued efforts in this direction will be necessary for fostering sustainable land use, improving food systems, and restoring ecosystem services for the benefit of both the environment and local communities.

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