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Biochar and Inorganic Fertilizers for Acidic Soil Management: Improving Soil Properties and Potato Productivity in Ethiopia

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ABSTRACT

This case study investigates the combined application of coffee husk biochar and inorganic fertilizers to improve soil properties and potato productivity on acidic soils in Southwestern Ethiopia. Soil acidity and low fertility due to nutrient leaching coupled with limited inorganic fertilizer use severely constrain crop yields in the region. The research tested four levels of biochar (0, 2.5, 5, and 7.5 t ha^{-1}) with four rates of inorganic nitrogen and phosphorus fertilizers (0, 75%, 100%, and 125% of recommended rates) in a randomized complete block design. Results demonstrated that combining 7.5 t ha^{-1} biochar with recommended NP fertilizer (165 kg N and 60 kg P ha^{-1}) significantly improved soil pH (from 4.87 to 6.47), organic matter content (71% increase), cation exchange capacity (52.58% increase), total nitrogen (39.28% increase), and available phosphorus (133.2% increase) compared to using inorganic fertilizer alone. This soil improvement corresponded with a 28.99% increase in potato tuber yield. The findings highlight biochar's potential as a sustainable soil amendment for ameliorating acidic soils through multiple beneficial mechanisms beyond simple pH adjustment, offering a promising approach for sustainable soil fertility management in tropical agricultural systems.

KEYWORDS

Biochar, Soil Acidity, Potato, Coffee Husk, Soil Fertility, Ethiopia, Inorganic Fertilizer, Sustainable Agriculture

INTRODUCTION

Soil acidity coupled with low soil fertility due to nutrient leaching are major constraints to agricultural productivity across Southwestern Ethiopia. The region's soils are characterized by Acrisols with a sub-surface layer of accumulated kaolinitic clay in the order Oxisol, exhibiting low cation exchange capacity, low base saturation, and low pH values. The experimental site soil was strongly acidic (pH 4.87) with loam texture, medium cation exchange capacity (22.12 meq/100g), low organic matter content (3.38%), medium total nitrogen (0.17%), and very low available phosphorus (3.41 ppm).

Potato (*Solanum tuberosum* L.) is the third most consumed crop globally after rice and wheat, with significant value for food security in Ethiopia due to its ability to mature earlier than most other crops during critical food shortage periods. While Ethiopia has suitable climatic and edaphic conditions for potato production, actual yields (14 ton ha^{-1}) remain far below attainable yields (30 ton ha^{-1}), largely due to poor soil fertility and suboptimal fertilizer application. Potatoes require balanced nutrient management without which growth and yield become remarkably low. Nitrogen is required in large amounts to maintain optimum shoot and tuber growth, while phosphorus requirements are higher for potatoes compared to many other crops due to their shallow and sparse root hair system.

Traditional approaches to address soil acidity include liming and compost application. Recently, biochar has gained attention as an alternative soil amendment that can reduce soil acidity and increase nutrient availability over longer periods. Biochar is produced through thermal degradation of organic materials under limited oxygen (pyrolysis). Despite its potential benefits, research on biochar application, particularly in combination with inorganic fertilizers on acidic tropical soils in Ethiopia, remains limited.

Thus, this case study examines how coffee husk biochar application with inorganic fertilizers improves acidic soil properties and potato productivity in Southwestern Ethiopia, providing a sustainable approach to addressing soil acidity constraints in tropical agricultural systems.

MATERIALS AND METHODS

Experimental Site

The field experiment was conducted at Gecha, Andiracha district, Southwestern Ethiopia (7.598779° latitude, 35.405884° longitude) at an elevation of 2039 m above sea level. The area receives high rainfall (1800-2200 mm annually) with mean annual temperatures between 15.1-27.5°C.

Biochar Production and Characterization

Coffee husks were used as feedstock for biochar production through fast pyrolysis at 350°C with a one-hour retention time at Jimma University College of Agriculture and Veterinary Medicine. The resulting biochar was ground to pass through a 2 mm sieve to ensure uniform particle size distribution for soil application. The biochar had a pH of 9.4, high organic carbon (18.01%), organic matter (31.06%), and CEC (63.23 meq/100g), as well as substantial total nitrogen (1.55%) and available phosphorus (13.63 ppm).

Experimental Design and Treatments

The experiment employed a randomized complete block design (RCBD) with three replications. Treatments consisted of four levels of biochar (0, 2.5, 5, and 7.5 t ha^{-1}) and four fertilizer rates:

- Control (0 N, 0 P)
- 123.75 kg N ha^{-1} and 45 kg P ha^{-1} (75% of recommended)
- 165 kg N ha^{-1} and 60 kg P ha^{-1} (100% of recommended)

- 206.25 kg N ha^{-1} and 75 kg P ha^{-1} (125% of recommended)

Each plot measured 3 m × 3 m with plant-to-plant and row-to-row spacing of 30 cm and 75 cm, respectively. Biochar was uniformly incorporated into the soil before planting. Nitrogen was applied in the form of urea and phosphorus in the form of Triple Super Phosphate (TSP) by side dressing at the time of planting.

Soil Analysis

Composite soil samples were collected from the upper 0-30 cm depth before planting and after harvest. Laboratory analyses determined:

- Soil texture (hydrometer method)
- Soil pH (potentiometrically using 1:2.5 soil to water ratio)
- Cation exchange capacity (ammonium acetate method)
- Organic matter content (wet oxidation method)
- Total nitrogen (Micro-Kjeldhal digestion)
- Available phosphorus (Bray II and Olsen extraction methods)

RESULTS

Effects On Soil Physicochemical Properties

The combined application of biochar and inorganic NP fertilizers significantly ($p<0.01$) affected soil pH, cation exchange capacity (CEC), soil organic matter content, total nitrogen, and available phosphorus.

Soil pH: The highest pH value (6.47) was recorded with 7.5 t ha^{-1} biochar combined with 165 kg N and 60 kg P ha^{-1}, representing a 32% increase over the control (pH 4.90). Importantly, applying inorganic fertilizers alone without biochar showed no significant effect on soil pH.

Cation Exchange Capacity (CEC): The highest CEC (38.52 meq/100g soil) was observed with 7.5 t ha^{-1} biochar and 206.25 kg N and 75 kg P ha^{-1}, representing a 63.9% increase compared to the control (23.50 meq/100g soil) and a 52.58% increase compared to the same rate of NP alone.

Soil Organic Matter: Combined application of 7.5 t ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1} resulted in the highest organic matter content (7.56%), showing a 71% increase compared to applying the same NP rate without biochar.

Total Nitrogen: The highest total nitrogen content (0.39%) was found in soil treated with 7.5 t ha^{-1} biochar and 206.25 kg N and 75 kg P ha^{-1}, representing a 39.28% increase over the same fertilizer rate without biochar.

Available Phosphorus: The highest available P (10.71 mg kg^{-1}) was measured in soil treated with 7.5 t ha^{-1} biochar and 206.25 kg N and 75 kg P ha^{-1}, showing a dramatic 133.2% increase over the same NP rate without biochar. The control plots had the lowest available P (3.51 mg kg^{-1}).

Effects on Potato Growth and Productivity

Tuber Yield: Combined application of 7.5 t ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1} produced the highest total tuber yield (42.64 t ha^{-1}), representing a 28.99% increase over recommended NP fertilizer alone (33.08 t ha^{-1}) and a 76.6% increase over the control (24.14 t ha^{-1}).

Marketable Tuber Yield: The same treatment (7.5 t ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1}) also produced the highest marketable tuber yield (40.80 t ha^{-1}), which was 30.85% higher than applying the same rate of NP alone (31.18 t ha^{-1}) and 85.3% higher than the control (22.02 t ha^{-1}).

Harvest Index: Application of 7.5 t ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1} resulted in the highest harvest index (0.64), representing a 77.8% increase over application of 206.25 kg N and 75 kg P ha^{-1} alone (0.36) and a 93.9% increase over the control (0.33).

Total Dry Biomass: The highest dry biomass yield (21.16 t ha^{-1}) was also recorded from plots treated with 7.5 t ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1}, showing a 25.65% increase over application of 206.25 kg N and 75 kg P ha^{-1} without biochar (16.84 t ha^{-1}) and a 63.6% increase over the control (12.93 t ha^{-1}).

The results indicate strong synergistic effects between biochar and inorganic NP fertilizers. Biochar's high alkalinity, porosity, and nutrient content help improve soil conditions, leading to enhanced fertilizer use efficiency and crop yields. This aligns with sustainable intensification goals in tropical agriculture.

CONCLUSIONS AND SOIL MANAGEMENT RECOMMENDATIONS

This case study demonstrates that combined application of coffee husk biochar and inorganic fertilizers can significantly improve soil properties and potato productivity on acidic soils in Southwestern Ethiopia. Key soil management recommendations include:

- Apply coffee husk biochar at 7.5 t ha^{-1} with recommended inorganic fertilizers (165 kg N and 60 kg P ha^{-1}) for optimal soil improvement and crop yield. This combination provided the best balance of soil property improvements and yield enhancement.
- Use biochar as a soil amendment to ameliorate acidic soils instead of or in addition to traditional liming. The alkalinity of biochar (pH 9.4) effectively increases soil pH, acting as a liming agent while providing additional benefits beyond soil pH adjustment.
- Incorporate biochar to improve soil nutrient retention in soils prone to leaching. Biochar's high CEC helps retain nutrients in the root zone, reducing losses through leaching and increasing fertilizer use efficiency.
- Adopt biochar as a long-term soil improvement strategy. Biochar remains stable in soil for longer periods compared to other organic amendments, providing lasting benefits to soil quality and fertility.
- Develop low-cost biochar production techniques to ensure economic viability. Coffee processing facilities could integrate biochar production to convert waste husks into valuable soil amendments.

The study highlights that biochar's benefits on soil properties extend beyond simple pH adjustment, improving overall soil fertility through multiple mechanisms, including increased CEC, organic matter content, and enhanced nutrient availability. The synergistic effect of combining biochar with inorganic fertilizers represents a promising approach for sustainable intensification of crop production on acidic soils.

This case also has broader implications for sustainable development. It contributes directly to several Sustainable Development Goals (SDGs). It supports SDG 2 (Zero Hunger) by enhancing crop productivity on marginal and degraded soils. It advances SDG 12 (Responsible Consumption and Production) by promoting the recycling of agricultural waste through the transformation of coffee husks into biochar. Finally, it contributes to SDG 15 (Life on Land) by improving soil health and supporting the restoration of degraded agricultural lands.

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