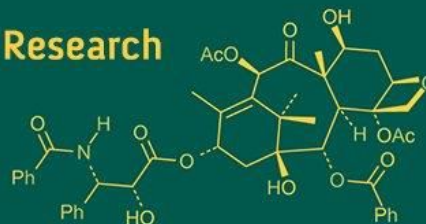
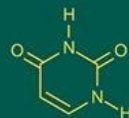


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Quality characterization of paddy straw biochar produced in open-kiln drum method and its potential for soil application

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Abstract

Biochar derived from agricultural residues has emerged as a sustainable soil amendment for improving soil health, enhancing crop productivity, and contributing to carbon sequestration. This experiment studied the physicochemical quality of paddy straw biochar produced using a traditional open-kiln drum method, a low-cost technique commonly adopted by farmers. The biochar was characterized for pH, electrical conductivity (EC), ash content, fixed carbon, volatile matter, bulk density, and nutrient composition. The paddy straw biochar exhibited alkaline pH (9.4), moderate EC (1.52 dS m^{-1}), high carbon content (64.8%), ash content (23.2%), and low bulk density (0.28 g cm^{-3}). Essential plant nutrients such as N, P, K, Ca, and Mg were present in significant amounts. These properties indicate that paddy straw biochar can improve soil pH, increase nutrient retention, and enhance soil physical conditions. The study concludes that biochar produced through farmer-friendly methods can be a promising amendment for acidic and nutrient-poor soils.

Keywords: Paddy straw biochar, open-kiln drum method, soil amendment, biochar quality, agricultural residue management

1. Introduction

Agricultural residue management, especially paddy straw, poses a major challenge across South Asia. Annually, India generates ~112-150 million tonnes of rice straw, of which a considerable portion is burned in open fields, contributing to severe air pollution, greenhouse gas emissions, and soil degradation (Gupta *et al.*, 2021; Singh *et al.*, 2020) [5, 12]. Transforming crop residues into biochar through pyrolysis gives an environmentally sound and agronomically beneficial solution. Biochar is a stable, carbon-rich material produced by thermal decomposition of biomass under limited oxygen (Lehmann & Joseph, 2015) [7]. Biochar's structure enhances soil fertility by improving cation exchange capacity, nutrient retention, water holding capacity, and reducing soil acidity (Major *et al.*, 2010; Mukherjee & Lal, 2013) [8, 9]. Among various biomass resources, paddy straw is abundant, renewable, and easily available, making it ideal for decentralized biochar production. Due to limited access to costly pyrolysis units, farmers often use open-kiln drum methods, which are simple, low-cost, and viable at field scale (Pandit *et al.*, 2020) [11]. However, the quality attributes of biochar produced using such traditional methods vary depending on feedstock, pyrolysis temperature, and process conditions (Cao & Harris, 2010) [1]. Hence, assessing the quality parameters of paddy straw biochar produced through field-level methods is essential for ensuring its effectiveness in soil application. This experiment emphasise on the quality characterization of paddy straw biochar produced in an open-kiln drum, evaluating its physicochemical properties and discussing its potential benefits for soil health, particularly in acidic and low-fertility conditions such as those prevalent in Eastern India.

2. Materials and Methods

2.1 Feedstock Collection

Paddy straw (*Oryza sativa* L.) was collected from rice fields, cleaned to remove soil and foreign materials, sun-dried, and stored in a dry environment until biochar production.

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2.2 Biochar Production Using Open-Kiln Drum Method

The biochar was produced using a 200-L perforated metal drum to maintain controlled airflow under limited oxygen. The paddy straw was densely packed and ignited from the top to allow a downward charring process. Pyrolysis temperatures ranged between 350–450 °C monitored using a handheld infrared thermometer. Once charring reached two-thirds depth, the drum was sealed to restrict oxygen entry and prevent complete combustion. The resulting char was quenched with water, dried, crushed, and sieved through a 2-mm mesh for laboratory analysis.

2.3 Biochar Characterization

The biochar samples were analyzed using established methods. pH and EC were determined in a 1:10 biochar-water suspension following Jackson (1973) [6]. Ash content, volatile matter, and fixed carbon were evaluated using proximate analysis (ASTM D1762-84). Bulk density was determined using the tapping method. Total carbon was estimated using the Walkley-Black wet oxidation method. Total nitrogen (N) was determined using the Kjeldahl method, phosphorus (P_2O_5) using the vanadomolybdate method, and potassium (K_2O), calcium (Ca), and magnesium (Mg) using flame photometry.

3. Results and Discussion

The physicochemical characterization of paddy straw biochar produced through the open-kiln drum method shows significant alterations in material quality compared to the original feedstock, confirming its suitability as a soil amendment. The biochar showed a strongly alkaline pH of 9.4, consistent with cereal-residue biochars produced under medium pyrolysis temperatures (350–450 °C). High pH values generally arise due to thermal degradation of acidic functional groups and concentration of basic cations such as Ca^{2+} , Mg^{2+} , and K^+ (Lehmann & Joseph, 2015) [7]. Such alkalinity is particularly beneficial for ameliorating acidic soils, especially in regions where soil acidity constrains nutrient availability. Electrical conductivity (EC) measured 1.52 dS m^{-1} , indicates moderate salinity levels. This is within the acceptable threshold for agricultural application and suggests that the biochar has a substantial fraction of soluble mineral ions without posing toxicity risks. According to Chan *et al.* (2007) [2], EC values between 1–3 dS m^{-1} in biochar enhance nutrient availability while remaining safe for most crops. The bulk density of 0.28 g cm^{-3} indicate its lightweight and porous structure, which can improve soil porosity, decrease compaction, and enhance water infiltration when applied to heavy-textured soils. This finding aligns with earlier reports that low-density biochars improve soil aeration and root penetration (Downie *et al.*, 2009) [3].

Proximate analysis showed 23.2% ash, 12.6% volatile matter, and 64.8% fixed carbon, indicating a stable carbonaceous structure with slow decomposition rates. High fixed carbon content is typical of biochars produced at mid-range temperatures and contributes to long-term carbon sequestration (Spokas, 2010) [13]. The ash fraction, equivalent to 232 g kg^{-1} , is rich in mineral nutrients and contributes to the liming potential of the biochar. The total carbon content was 58.4% (584 g kg^{-1}), indicating a strong carbonization efficiency. High carbon concentrations help enhance soil aggregation, microbial habitat formation, and overall soil organic carbon levels (Novak *et al.*, 2009) [10].

The nutrient analysis showed moderate concentrations of nitrogen (7.8 g kg^{-1}), available P_2O_5 (4.2 g kg^{-1}), and available K_2O (16.2 g kg^{-1}). Potassium content was especially high, typical for straw-derived biochars, and beneficial for improving crop stress resistance and enzymatic functioning. High K availability in cereal-residue biochars has been reported in similar studies (Gaskin *et al.*, 2008) [4]. Calcium and magnesium contents, 12.8 g kg^{-1} and 4.6 g kg^{-1} respectively, contribute to the biochar's liming effect and enhancement of soil cation exchange capacity.

Overall, the results indicate that paddy straw biochar produced through open-kiln pyrolysis holds potential for agricultural application. Its chemical characteristics suggest positive impacts on soil fertility, nutrient cycling, soil structure, and long-term carbon storage. Similar findings have been documented in studies evaluating the agronomic benefits of straw-derived biochars in tropical and subtropical soils (Yuan & Xu, 2011) [14]. The combination of alkalinity, nutrient enrichment, and high carbon stability positions this biochar as a promising amendment for sustainable soil management and climate-resilient farming.

Table 1: Physicochemical properties of paddy straw biochar

Parameter	Value (%)	Value in g/kg
pH	9.4	—
EC (dS m^{-1})	1.52	—
Bulk density (g cm^{-3})	0.28	—
Ash content (%)	23.2	232 g/kg
Volatile matter (%)	12.6	126 g/kg
Fixed carbon (%)	64.8	648 g/kg
Total carbon (%)	58.4	584 g/kg
Nitrogen (%)	0.78	7.8 g/kg
Available P_2O_5 (%)	0.42	4.2 g/kg
Available K_2O (%)	1.62	16.2 g/kg
Calcium (%)	1.28	12.8 g/kg
Magnesium (%)	0.46	4.6 g/kg

Conclusion

The paddy straw biochar produced using a simple open-kiln drum method showed highly favorable characteristics for agricultural use. Its alkaline pH, moderate EC, and low bulk density indicate strong potential for improving soil structure and reducing soil acidity. High fixed carbon and total carbon contents confirm long-term stability and carbon sequestration capacity. The nutrient profile—particularly potassium, calcium, and magnesium—suggests that the biochar not only enhances soil physical properties but also supplies essential plant nutrients. With considerable ash and mineral content, this biochar can play a significant role in enhancing nutrient retention, increasing cation exchange capacity, and improving soil fertility in degraded and nutrient-poor soils. Overall, the results establish paddy straw biochar as a sustainable and effective amendment for promoting soil health and supporting climate-resilient agriculture.

Future Scope of the Research

The present study establishes the physicochemical quality of paddy straw biochar and its potential as a low-cost soil amendment. However, several avenues remain open for advancing scientific understanding and field-level application:

- 1. Long-term field experiments:** Multi-season and multi-location trials are needed to determine the long-term effects of paddy straw biochar on soil fertility, nutrient

- cycling, crop productivity, and carbon sequestration under varied agro-climatic conditions.
2. **Optimization of production conditions:** Further research should focus on optimizing pyrolysis temperature, residence time, and airflow in the open-kiln drum system to improve carbon stability, nutrient retention, and biochar yield.
 3. **Biochar-nutrient interactions:** Assessing the interaction of paddy straw biochar with mineral fertilizers, compost, and organic manures can help develop integrated nutrient management strategies suited for acidic and nutrient-deficient soils.
 4. **Impact on soil biological activity:** Studies on microbial community structure, enzyme activities, and soil faunal response will provide deeper insight into how paddy straw biochar influences soil biological health.
 5. **Environmental and economic assessment:** Life cycle assessment (LCA), carbon budgeting, and cost-benefit analysis should be conducted to evaluate the environmental benefits and economic feasibility of adopting biochar at large scale.
 6. **Development of farmer-friendly biochar units:** Engineering improvements in open-kiln systems or low-cost portable pyrolysis units can enhance efficiency, reduce emissions, and make biochar production more accessible to smallholder farmers.
 7. **Use in degraded land reclamation:** Future studies may explore the application of paddy straw biochar for rehabilitating acidic, eroded, or metal-contaminated soils due to its liming effect and high carbon content.
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