***Review Article***

**Impacts of Sugarcane Biochar on Soil Properties and Mung Bean (*Vigna radiata* L.) Productivity: A Comprehensive Review**

**ABSTRACT**

The increasing pressure on agricultural systems to produce more food sustainably has emphasized the importance of soil health restoration and effective agricultural waste management. **Sugarcane bagasse**, a fibrous by-product of sugar industries, represents a renewable and underutilized biomass that can be transformed into **biochar** a carbon-rich material known for its ability to improve soil quality and enhance crop productivity. This review focuses on the **impact of sugarcane bagasse-derived biochar** on soil physicochemical properties and the **growth and yield of mung bean (*Vigna radiata* L.)**, a short-duration legume essential for protein security and soil fertility improvement through nitrogen fixation. The article synthesizes current knowledge on biochar production methods (slow pyrolysis, fast pyrolysis, and hydrothermal carbonization), its structural and chemical properties, and its role in soil amendment. Biochar significantly enhances soil pH, cation exchange capacity, water retention, and microbial biomass. These changes improve nutrient retention (N, P, K, and micronutrients), reduce nutrient leaching, and enhance the efficiency of both organic and inorganic fertilizers. In mung bean cultivation, such improvements lead to enhanced germination, nodulation, root growth, biomass accumulation, and seed yield. Furthermore, biochar contributes to long-term **carbon sequestration** and climate mitigation by stabilizing organic carbon and reducing greenhouse gas emissions. The review also explores future directions including the integration of biochar with **climate-smart agriculture**, use of **biochar blends** (e.g., compost and nano-biochar), and the importance of **field-level validation, site-specific application strategies**, and **economic feasibility analysis**. Overall, sugarcane biochar offers a sustainable, scalable solution to enhance soil fertility and crop productivity, particularly in legume-based farming systems.

***Keywords:*** *Sugarcane, Bagasse, Biochar, Mung bean, Soil fertility, Nutrient retention, Sustainable agriculture*

1. **INTRODUCTION**

The global agricultural sector is currently navigating a multitude of interlinked challenges including rising food demand, declining soil fertility, climate change, and increasing agricultural waste generation. As the world population continues to expand, projected to surpass 9.7 billion by 2050, the demand for food is expected to increase by over 60% (Oluwole et al., 2023). This mounting pressure not only demands higher productivity but also compels a re-evaluation of traditional farming practices that have historically contributed to environmental degradation through unsustainable land use, excessive reliance on chemical inputs, and poor waste management. One of the most pressing issues is the growing volume of **agricultural waste**, particularly from crop residues and agro-industrial by-products. Improper disposal of such residues often by burning or dumping results in soil nutrient depletion, water contamination, air pollution, and greenhouse gas emissions (Koul et al., 2022; Prado-Acebo et al., 2024). Concurrently, soil degradation due to erosion, nutrient mining, and loss of organic matter has emerged as a critical constraint to sustainable crop production in many regions, especially in resource-poor farming systems (Srinivasarao et al., 2021). Restoring and maintaining **soil health** is therefore a cornerstone of resilient, climate-smart agriculture.

Against this backdrop, **biochar** has gained significant attention as a viable solution to multiple agro-environmental problems. Biochar is a carbon-rich, porous material produced by pyrolysis of organic biomass under low-oxygen conditions (Lu et al., 2025). Its potential to enhance **soil physicochemical properties**, retain nutrients, suppress greenhouse gas emissions, and sequester carbon makes it a promising tool for improving agricultural sustainability (Semida et al., 2019; Shoudho et al., 2024). Among various biomass sources, **sugarcane bagasse** the fibrous residue left after juice extraction from sugarcane stands out due to its high lignocellulosic content, availability in large volumes, and favourable carbon composition (Mubarak et al., 2024). Converting sugarcane bagasse into biochar represents a circular economy strategy by transforming waste into a valuable soil amendment. This review aims to provide a comprehensive synthesis of recent research on the **effects of sugarcane bagasse-derived biochar** on soil health and the growth and productivity of **mung bean (*Vigna radiata* L.)**, an important pulse crop known for its short duration, nitrogen-fixing ability, and high nutritional value. Specific focus is placed on how biochar improves nutrient availability, prevents leaching losses, enhances soil microbial activity, and influences mung bean yield attributes under varying application rates. The review also discusses biochar’s role in environmental remediation and its potential integration into sustainable farming practices. By highlighting current findings, challenges, and knowledge gaps, this review serves as a scientific foundation for future biochar-based soil management strategies in legume-based cropping systems.

**2. SUGARCANE BAGASSE: A RENEWABLE FEEDSTOCK**

Sugarcane (Saccharum officinarum L.) is one of the most widely cultivated industrial crops globally, primarily for sugar and bioethanol production. According to the USDA and FAO estimates, the global production of sugarcane has consistently exceeded **1.9 billion metric tons annually**, with **Brazil, India, China, Thailand**, and **Pakistan** accounting for more than 70% of the total output (Raza et al., 2019). India alone contributes approximately 29.66 million metric tons, ranking among the top global producers. This immense scale of production leads to the generation of substantial quantities of agricultural by-products, notably **sugarcane bagasse (SCB)** the fibrous residue left after juice extraction.

For every ton of sugarcane processed, nearly **280 kg of wet bagasse** is produced, making it a major agro-industrial residue. **Sugarcane bagasse** is primarily composed of **cellulose (32–45%)**, **hemicellulose (21–30%)**, and **lignin (20–25%)**, along with small amounts of ash, waxes, and extractives (Wani et al., 2023). Its **high carbon content**, **low bulk density**, and **rich lignocellulosic composition** make it a promising biomass for bio-based applications. Physicochemical properties such as **high fixed carbon**, **moderate ash**, and **low hydrogen content** render it ideal for **biochar production via pyrolysis**.

Despite its potential, much of the sugarcane bagasse produced remains **underutilized or poorly managed**. While a portion is combusted in sugar mills as a low-efficiency fuel, significant volumes are **stockpiled or discarded**, often leading to **open burning** or **landfilling**. These disposal methods contribute to **air pollution, fire hazards**, and **environmental contamination**, undermining the sustainability of the sugarcane industry. The **flammable nature** of dry bagasse, combined with its bulkiness and limited degradability, also poses logistical and ecological risks. Converting sugarcane bagasse into **biochar** offers a sustainable and value-added alternative to conventional disposal. Through **controlled thermochemical processes** such as pyrolysis or hydrothermal carbonization, SCB can be transformed into a stable, carbon-rich material suitable for **soil amendment, environmental remediation**, and even **energy recovery (**Begum et al., 2024**)**. This not only addresses the **waste management challenges** associated with bagasse but also aligns with circular economy principles by **returning carbon to the soil**, enhancing **soil fertility**, and contributing to **climate change mitigation**. Furthermore, utilizing SCB for biochar production allows sugarcane-growing regions particularly in tropical and subtropical zones to locally manage waste, reduce dependence on external soil inputs, and build climate-resilient farming systems. This integration of **waste valorization with soil health improvement** makes sugarcane bagasse a highly strategic feedstock for sustainable agriculture.

### ****3.**** ****BIOCHAR PRODUCTION FROM SUGARCANE BAGASSE****

**3.1** **Overview of Biochar: Definition, History, and Relevance**

**Biochar** is a stable, carbon-rich material produced through the thermochemical conversion of organic biomass under low or zero oxygen conditions a process known as **pyrolysis**. Historically, the concept of biochar can be traced back to the **Terra Preta soils** of the Amazon basin, where ancient civilizations enriched nutrient-deficient tropical soils using charcoal and organic matter, leading to long-lasting fertility (Yang & Yang, 2024). Modern science has since revisited this practice, recognizing biochar as a potential tool for **soil amelioration**, **carbon sequestration**, and **sustainable agriculture**. The global relevance of biochar lies in its ability to **improve soil structure**, increase **nutrient retention**, buffer **soil acidity**, and **enhance microbial activity**, while simultaneously offering a **long-term carbon sink**. Biochar derived from sugarcane bagasse not only addresses waste disposal but also provides a renewable soil amendment suited to various cropping systems, including legumes like mung bean.

**3.2 Thermochemical Techniques for Biochar Production**

Biochar from sugarcane bagasse can be produced using several **thermochemical conversion methods**, each affecting the quality, stability, and nutrient content of the resulting material: **Slow Pyrolysis**is the most commonly used technique for biochar production. It involves heating biomass at **300–600°C** over **several hours** in the absence of oxygen. Slow pyrolysis maximizes **biochar yield** (typically 30–35% by weight), making it suitable for soil applications. It produces biochar with **high fixed carbon**, **stable aromatic structures**, and **good porosity**, enhancing its persistence in soil and effectiveness as an amendment. **Fast/Flash Pyrolysis**method operates at **higher temperatures (450–700°C)** and with **short residence times** (seconds to minutes), yielding more **bio-oil** and **syngas** but significantly less biochar (10–15%) (Amenaghawon et al., 2021). While the biochar produced may have higher surface area, the method is more energy-intensive and less efficient for biochar-focused objectives.**Hydrothermal Carbonization (HTC)**performed under **high-pressure, low-oxygen, aqueous conditions** at **180–250°C**, particularly suitable for **wet biomass** like fresh sugarcane bagasse (Hussin et al., 2023). The product, known as **hydrochar**, has high energy density but differs chemically from pyrolytic biochar. Although it shows promise for energy and adsorptive applications, its agronomic effectiveness is generally lower than that of pyrolytic biochar. Comparison of Thermochemical Methods for Biochar and Hydrochar Production from Biomass tabulated in Table 1.

**Table 1: Comparison of Thermochemical Methods for Biochar and Hydrochar Production from Biomass**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Method** | **Temp (°C)** | **Residence Time** | **Biochar Yield (%)** | **Advantages** | **Limitations** |
| **Slow Pyrolysis** | 300–600 | Several hours | 30–35 | High carbon stability; ideal for soil | Slower process; lower bio-oil yield |
| **Fast Pyrolysis** | 450–700 | Seconds to minutes | 10–15 | Higher bio-oil output | Low biochar yield; energy intensive |
| **Hydrothermal Carbon** | 180–250 | 30–240 minutes | 50–80 (as hydrochar) | Suitable for wet biomass; low energy input | Produces hydrochar with less soil benefit |

**3.3** **Activation Techniques for Functional Biochar**

To enhance the surface properties and adsorption potential of biochar especially for pollutant removal or nutrient interactions various **activation techniques** are used: **Chemical Activation (e.g., KOH, NaOH)** Treating biochar with potassium hydroxide (KOH) or sodium hydroxide (NaOH) increases its **surface area, porosity**, and **functional groups (**Panwar & Pawar, 2022**)**. This makes it highly effective for **nutrient adsorption**, **cation exchange**, and **heavy metal immobilization**. **Magnetic Activation (e.g., Fe-based particles)** Incorporating iron oxides (Fe₂O₃, Fe₃O₄) into sugarcane biochar results in **magnetic biochar**, which exhibits high efficiency in **removing heavy metals** (e.g., Pb, Cr) from soil and water and is easily recoverable (Cheam, 2018). These types of biochar also aid in **redox reactions** and **soil detoxification**. **Steam and CO₂ where,** Physical activation using steam or carbon dioxide helps develop a **well-connected pore structure**, making biochar suitable for **adsorption-based applications** and improving its interaction with soil microbes and nutrients. Activation not only improves the **adsorptive performance** of biochar but also tailors it for specific applications whether for **soil fertility**, **water purification**, or **pollutant remediation**.

**4****. PHYSICOCHEMICAL PROPERTIES OF SUGARCANE BIOCHAR**

**4.1** **Structural and Chemical Characteristics**

Sugarcane bagasse-derived biochar exhibits a unique combination of **physicochemical properties** that make it highly effective for agricultural and environmental applications. One of the most notable features is its **high fixed carbon content**, often exceeding 70–80% depending on pyrolysis conditions, which contributes to the long-term stability of biochar in soil. This high carbon concentration not only supports **carbon sequestration** but also improves **soil organic carbon levels** over time. Another key attribute is its **high porosity and large specific surface area**, which allow the biochar to retain water and nutrients effectively. These properties are crucial in enhancing the soil’s **water-holding capacity** and **nutrient retention**, especially in sandy or degraded soils. Sugarcane biochar typically has a **slightly alkaline to neutral pH** (ranging from 7 to 9), which is beneficial for **ameliorating acidic soils** and promoting favorable conditions for root growth and microbial activity. The **cation exchange capacity (CEC)** of sugarcane biochar is another vital characteristic that enables it to adsorb and hold essential nutrients such as **NH₄⁺, K⁺, Ca²⁺, and Mg²⁺**, preventing their leaching (Hai et al., 2025). Studies have reported CEC values ranging from **10 to 50 cmol(+)/kg**, depending on the production temperature and feedstock pretreatment.

**4.2 Surface Functional Groups**

The surface chemistry of sugarcane biochar is enriched with diverse **oxygen-containing functional groups**, which play a key role in its reactivity and nutrient interaction capacity. These include: **Carboxylic groups (-COOH)**: Contribute to cation exchange and metal chelation, **Phenolic groups (-OH)**: Provide antioxidant and adsorption activity, **Lactones**: Improve interaction with acidic or basic soil components (Nobahar et al., 2021). These functional groups are primarily located on the outer surfaces and pores of the biochar matrix, influencing its **acid-base behavior**, **adsorption capacity**, and interaction with **plant roots and microbes**.

**4.3 Biochar vs. Hydrochar**

While both biochar and **hydrochar** are carbon-rich materials derived from biomass, their **composition and characteristics differ significantly** due to the contrasting production techniques. **Biochar** is generally more suitable for **long-term soil amendment**, while **hydrochar** may be better for short-term nutrient release or as a precursor for activated carbon. Comparative Properties of Biochar (Pyrolysis) and Hydrochar (Hydrothermal Carbonization) Derived from Biomass tabulated in Table 2.

**Table 2: Comparative Properties of Biochar (Pyrolysis) and Hydrochar (Hydrothermal Carbonization) Derived from Biomass**

|  |  |  |
| --- | --- | --- |
| **Property** | **Biochar (Pyrolysis)** | **Hydrochar (HTC)** |
| **Production Temp. (°C)** | 300–700 | 180–250 |
| **Porosity & Surface Area** | High | Moderate to low |
| **pH** | Neutral to Alkaline | Acidic to Neutral |
| **Fixed Carbon** | High (60–85%) | Moderate (40–60%) |
| **Functional Groups** | Rich in aromatic, stable structures | Contains more aliphatic, labile compounds |
| **Soil Stability** | Excellent (long-term) | Lower (prone to microbial degradation) |

**4.4** **Effect of Pyrolysis Temperature and Feedstock Treatment**

Pyrolysis temperature is a critical determinant of the final quality and functionality of biochar. As temperature increases: **Volatile matter decreases, Fixed carbon and ash content increase and Surface area and pore development improve.** Biochar produced at **higher temperatures (500–700°C)** tends to have greater aromaticity and carbon stability but lower amounts of surface functional groups (Tan et al., 2021). In contrast, **low-temperature biochars (300–400°C)** retain more labile compounds and functional groups, which can be beneficial for **nutrient availability and microbial stimulation** in the short term. Additionally, **pre-treatment of sugarcane bagasse** (e.g., drying, size reduction, chemical activation) can significantly influence biochar characteristics. For example, **alkali treatment (e.g., KOH)** can enhance pore development and surface reactivity, while **iron impregnation** improves its capacity for **heavy metal adsorption**.

**5.** **IMPACT OF SUGARCANE BIOCHAR ON SOIL PROPERTIES**

The application of biochar, particularly that derived from sugarcane bagasse, significantly influences a range of **soil physicochemical and biological properties**, contributing to improved soil health and crop productivity. These improvements are especially relevant in the context of **sustainable legume cultivation**, such as mung bean, which thrives in nutrient-balanced, biologically active soils.

**5.1 Soil pH and Buffering Capacity**

Sugarcane biochar typically possesses a **neutral to slightly alkaline pH** (7–9), making it highly effective for **ameliorating acidic soils**, which are common in tropical and subtropical regions. When added to acidic soils, biochar can increase the pH, thereby **neutralizing toxic aluminum ions**, improving **nutrient solubility**, and creating favorable conditions for root growth and microbial activity (Shetty et al., 2021). Moreover, the presence of **carbonate and basic functional groups** in biochar imparts **buffering capacity**, stabilizing soil pH against sudden shifts caused by fertilizer or environmental changes.

**5.2 Cation Exchange Capacity (CEC)**

One of the most important functions of biochar in soil is its ability to enhance **cation exchange capacity (CEC)**. The porous structure and surface functional groups (carboxyl, phenolic) of sugarcane biochar allow it to **adsorb and retain essential nutrients** such as ammonium (NH₄⁺), potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺), thereby reducing their leaching losses (Saleh & Hedia, 2018). This improved nutrient retention not only supports plant nutrition but also increases fertilizer use efficiency—an important consideration in low-input farming systems.

**5.3 Water Holding Capacity and Aeration**

The porous microstructure of sugarcane bagasse-derived biochar enhances the **water retention** capacity of soils, particularly **light-textured or sandy soils**. The large surface area and internal pore networks enable the biochar to hold water and gradually release it, improving **plant water availability** during dry periods. Simultaneously, biochar improves **soil aeration** by loosening compacted soils and creating microhabitats for root development and microbial colonization. These physical improvements are especially beneficial for mung bean, which has a relatively shallow root system sensitive to water and air stress (Tutlani et al., 2023).

**5.4 Organic Matter and Microbial Activity**

Biochar addition can indirectly increase **soil organic matter (SOM)** through its interaction with crop residues, root exudates, and microbial biomass. Its high surface area and stability make it a **favourable habitat for beneficial soil microbes**, including **nitrogen-fixing bacteria** and **mycorrhizal fungi**. These microbes contribute to nutrient cycling, soil aggregation, and disease suppression. In legumes like mung bean, improved rhizosphere microbial activity translates into **enhanced nodulation and biological nitrogen fixation**, thus promoting sustainable yield gains without the excessive need for synthetic fertilizers.

**5.5 Carbon Sequestration and GHG Mitigation**

Biochar is a **highly recalcitrant form of organic carbon**, with residence times in soil ranging from decades to centuries. Its application leads to **long-term carbon sequestration**, effectively locking atmospheric CO₂ into stable soil carbon pools. Additionally, biochar can **reduce greenhouse gas (GHG) emissions** from soil by decreasing nitrous oxide (N₂O) emissions (due to nitrification suppression) and methane (CH₄) emissions in waterlogged soils (Wang et al., 2023). This environmental benefit is particularly significant in **climate-smart agriculture** initiatives aimed at mitigating the adverse impacts of global warming. The integration of sugarcane biochar into agricultural soils creates a synergistic improvement in **chemical balance**, **physical structure**, and **biological function**, making it a versatile amendment for building **resilient and productive agroecosystems**, particularly for mung bean cultivation.

**5.6 Biochar as a Soil Amendment for Sustainable Crop Production**

The transformation of agricultural biomass into biochar provides a sustainable strategy to improve soil quality and promote plant productivity. As illustrated in **Fig. 1,** plant-based residues such as sugarcane bagasse, coconut shells, and other lignocellulosic materials can be converted into biochar through pyrolysis. Once applied to soil, biochar plays a dual role enhancing both the **physicochemical** (e.g., pH, porosity, nutrient retention) and **biological** attributes (e.g., microbial diversity and activity) of soil. These improvements contribute significantly to overall **soil health,** which in turn supports robust **crop stand establishment** and enhances **crop yield (**Hussain et al., 2017**).** The integration of biochar into farming systems therefore represents a sustainable loop, converting plant waste into a valuable resource that supports both **agroecosystem resilience** and **crop productivity.**



**Fig. 1.** **Schematic representation of biochar production from plant biomass and its role in improving soil health and crop growth**

**6.** **EFFECTS OF SUGARCANE BIOCHAR ON GROWTH AND YIELD OF MUNG BEAN**

**6.1** **Relevance of Mung Bean in Cropping Systems and as a Protein Source**

Mung bean (Vigna radiata L.) is a fast-growing, short-duration leguminous crop widely cultivated in Asia and Africa. It plays a vital role in **diversifying cropping systems**, especially in **rice-wheat rotations**, by improving **soil fertility through biological nitrogen fixation** and fitting well into **intercropping and sequential cropping systems**. Beyond its agronomic value, mung bean serves as an **affordable protein source**, providing essential amino acids, iron, and vitamins to populations in developing countries. Its adaptability to marginal soils and semi-arid environments makes it a critical crop for food and nutritional security in smallholder farming systems.

**6.2 Enhancement of Germination and Root Development**

Sugarcane bagasse biochar positively influences **seed germination and early seedling vigor** by improving the **soil microclimate**, increasing **moisture availability**, and reducing **soil compaction**. The presence of macro- and micronutrients such as potassium, calcium, and iron in biochar-amended soil supports **radicle emergence and root elongation**. Improved aeration and water retention help maintain ideal conditions for early establishment, a critical phase in mung bean's life cycle. Studies have shown that moderate biochar application (e.g., 25 t/ha) can significantly boost germination rates and initial root biomass compared to untreated soils (Rab et al., 2016).

**6.3 Improvement in Nodulation and Nitrogen Fixation**

As a legume, mung bean relies heavily on its ability to **form symbiotic nodules with *Rhizobium spp*.**, which fix atmospheric nitrogen into plant-usable forms. Biochar creates a favourable habitat for rhizobia by increasing **soil pH**, enhancing **CEC**, and supplying **micronutrients** such as molybdenum and iron both essential for nitrogenase activity (Parasar & Agarwala, 2025). The porous structure of biochar also provides a refuge for rhizobial populations, enhancing their survival and activity near the root zone. Research has demonstrated that biochar amendments can increase the **number and size of nodules**, as well as **nitrogen fixation efficiency**, ultimately reducing the plant's dependency on synthetic N fertilizers. This contributes to **sustainable nutrient cycling** and better nitrogen economy in the cropping system.

**6.4 Biomass Accumulation and Seed Yield**

The cumulative impact of improved nutrient availability, water retention, and rhizobial activity results in higher **biomass accumulation** and **enhanced reproductive performance** of mung bean plants. Sugarcane biochar application at 25 t/ha has been reported to increase **pod length, grains per pod, 100-seed weight**, and **overall grain yield** compared to control treatments (see Table 3). In addition, biochar increases the **harvest index**, reflecting efficient partitioning of biomass into economic yield (Rab et al., 2016). These findings underscore the potential of sugarcane biochar to enhance both the **vegetative growth** and **reproductive output** of mung bean, offering a sustainable pathway to boost legume productivity under varying agro-ecological conditions.

**Table 3:** **Effect of Sugarcane Bagasse-Derived Biochar (25 t/ha) on Growth and Yield Attributes of Mung Bean (Vigna radiata L.)**

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Control** | **Biochar (25 t/ha)** |
| **Pods per plant** | 17.00 | 23.00 |
| **Pod length (cm)** | 6.00 | 9.20 |
| **Grains per pod** | 8.00 | 11.00 |
| **100-grain weight (g)** | 3.60 | 5.40 |
| **Grain yield (g/pot)** | 2.70 | 4.20 |
| **Harvest index (%)** | 12.30 | 14.87 |

**(Source: Rab et al., 2016)**

The application of sugarcane bagasse-derived biochar has been shown to significantly enhance the growth and yield attributes of mung bean (*Vigna radiata* L.). Biochar, when applied to soil at varying rates, improves soil fertility, nutrient retention, and microbial activity, ultimately influencing crop productivity. A study conducted by Rab et al. (2016) assessed the impact of different biochar application rates (0, 25, 50, 75, and 100 t/ha) on mung bean performance. The results indicated that a biochar rate of 25 t/ha was optimal, resulting in the highest number of pods per plant (23), pod length (9.2 cm), grains per pod (11), grain yield per pot (4.2 g), and harvest index (14.87%), compared to the control (Table 4). Higher application rates did not further enhance yield and, in some cases, showed a declining trend, possibly due to nutrient imbalances or physical alterations in soil structure. This suggests that moderate levels of sugarcane biochar can significantly improve mung bean yield by positively modifying soil properties and supporting plant physiological functions.

**7.** **BIOCHAR'S ROLE IN NUTRIENT AVAILABILITY AND FERTILITY**

**7.1** **Nutrient Retention (N, P, K, Micronutrients)**

Biochar derived from sugarcane bagasse plays a pivotal role in **improving soil nutrient status** through enhanced retention and reduced loss of both macro- and micronutrients. Its **high cation exchange capacity (CEC)**, arising from a porous structure and surface functional groups (e.g., carboxylic and phenolic), enables it to **adsorb essential nutrients** like **ammonium (NH₄⁺), nitrate (NO₃⁻), phosphate (PO₄³⁻), potassium (K⁺), calcium (Ca²⁺)**, and **magnesium (Mg²⁺) (**Dey et al., 2023**)**. This slows nutrient mobility in the soil and prevents rapid depletion from the rhizosphere. Additionally, sugarcane biochar often contains **intrinsic nutrients**, especially potassium, and small amounts of phosphorus, which directly contribute to the nutrient pool available to plants. Micronutrient retention particularly of **iron (Fe), zinc (Zn), and manganese (Mn)** is also enhanced, improving overall nutrient balance and supporting mung bean’s growth and reproductive functions.

**7.2 Prevention of Nutrient Leaching**

One of the key agronomic advantages of biochar is its capacity to **reduce nutrient leaching**, particularly in **sandy or coarse-textured soils** where water and nutrient losses are prevalent. Biochar particles physically **adsorb nitrate and phosphate ions**, slowing their movement beyond the root zone. This mechanism helps maintain nutrient availability during rainfall or irrigation events, enhancing **fertilizer use efficiency**. Experimental studies have shown that biochar-amended soils exhibit **lower nitrate concentrations in leachate**, indicating its ability to act as a **nutrient reservoir**. This is especially beneficial in mung bean systems, where effective nitrogen management is crucial for optimizing yield and nodulation.

**7.3 Interaction with Organic and Inorganic Fertilizers**

Biochar synergizes well with both **organic amendments (e.g., compost, manure)** and **inorganic fertilizers**. When applied in combination, biochar can buffer nutrient release, minimize **volatilization losses**, and **extend the availability of nutrients** throughout the crop growth cycle (Table 5). This interaction reduces the likelihood of nutrient shocks or imbalances while promoting a more stable nutrient supply for mung bean plants. Moreover, the **alkaline nature** of sugarcane biochar improves fertilizer efficiency in acidic soils by neutralizing soil acidity, enhancing phosphorus availability, and creating favorable conditions for **root nutrient uptake**. The co-application of biochar with organic inputs also enhances **soil microbial biomass and enzymatic activity**, further improving nutrient mineralization and uptake (Kumari et al., 2023).

**7.4 Synergistic Effects on Mung Bean Productivity**

The improvements in **soil fertility** directly translate into enhanced mung bean performance. Several studies, including that of Rab et al. (2016), have shown that biochar application increases **nodulation, pod number, grain weight**, and **total seed yield**. By retaining nutrients in the root zone and fostering a favorable rhizosphere environment, biochar allows mung bean plants to access nutrients more efficiently, especially under low-input conditions (Table 5). Furthermore, the presence of micronutrients and enhanced microbial activity contribute to **biological nitrogen fixation**, reducing dependency on synthetic N fertilizers. As a result, biochar contributes to **sustainable intensification**, enhancing mung bean yields while preserving soil health for future cropping cycles.

**7.5 Multifunctionality of Biochar in Agro-Environmental Systems**

As shown in **Fig. 2**, biochar plays an integrative role across several sectors of sustainable development. Derived from a variety of feedstocks such as **wood, agricultural residues, municipal waste, and kitchen waste (green waste)**, biochar production contributes to **waste valorization** and generates **co-products** like bio-oil and syngas both of which are renewable energy carriers. In agricultural systems, biochar improves **soil structure**, enhances **nutrient and water retention**, promotes **microbial activity**, and supports **plant growth**, which ultimately leads to better yields (Table 5). The **alkaline nature**, **porosity**, and **functional groups** on biochar surfaces aid in **heavy metal immobilization** through processes such as **surface complexation**, **electrostatic interaction**, **ionic exchange**, and **physical adsorption**. Additionally, biochar contributes significantly to **greenhouse gas mitigation** through **carbon sequestration**, as plant biomass absorbs CO₂ and stores it in a stable form within the soil. This makes biochar a strategic amendment not only for sustainable agriculture but also for **climate-smart soil management**.



**Fig. 2.** **Multifunctional roles of biochar derived from various waste sources**

**Table 4: Effect of Sugarcane Bagasse-Derived Biochar on Growth and Yield Attributes of Mung Bean (*Vigna radiata* L.)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Biochar Application Rate (t/ha)** | **Pods per Plant** | **Pod Length (cm)** | **Grains per Pod** | **100-Grain Weight (g)** | **Biological Yield (g/pot)** | **Grain Yield (g/pot)** | **Harvest Index (%)** |
| **0 (Control)** | 17.00 | 6.00 | 8.00 | 3.60 | 22.00 | 2.70 | 12.30 |
| **25** | 23.00 | 9.20 | 11.00 | 5.40 | 28.30 | 4.20 | 14.87 |
| **50** | 20.00 | 8.00 | 10.00 | 5.80 | 26.00 | 3.80 | 14.62 |
| **75** | 19.00 | 7.50 | 9.00 | 6.20 | 25.50 | 3.40 | 13.33 |
| **100** | 18.00 | 7.00 | 9.00 | 6.80 | 24.00 | 3.10 | 12.92 |

***(Source: Rab et al., 2016)***

 **Table 5. Biochar's Role in Nutrient Availability, Fertility, and Mung Bean Productivity**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Function** | **Mechanism/Effect** | **Outcome in Soil** | **Impact on Mung Bean Productivity** | **References** |
| **Nutrient Retention (N, P, K, Micronutrients)** | High CEC and porous structure adsorb and retain essential nutrients | Reduced nutrient loss; improved nutrient availability | Better root nutrition; increased nodulation and seed yield | Major et al., 2012; Rab et al., 2016 |
| **Prevention of Nutrient Leaching** | Adsorption of nitrate and phosphate; pH buffering | Lower leaching losses, particularly of N and K | Sustained nutrient supply over growth period; enhanced pod and seed set | Laird et al., 2010; Singh et al., 2024 |
| **Interaction with Organic/Inorganic Fertilizers** | Acts as a carrier; slows nutrient release; reduces volatilization | Improves fertilizer efficiency and reduces environmental loss | Enhanced biomass and yield per unit fertilizer applied | Uzoma et al., 2011; Arif et al., 2021 |
| **Synergistic Effects on Mung Bean Productivity** | Stimulates microbial activity and rhizobial colonization; supports root growth | Enhanced nitrogen fixation and uptake of macro- and micro-nutrients | Improved pod length, seed weight, harvest index, and total seed yield | Rab et al., 2016; Murtaza et al., 2023 |

**8. FUTURE PROSPECTS AND RESEARCH DIRECTIONS**

The emerging role of sugarcane bagasse-derived biochar in sustainable agriculture opens numerous opportunities for its broader integration into mainstream farming systems. However, several scientific, technological, and socio-economic aspects require further exploration to maximize its impact, particularly in legume-based systems like mung bean.

**8.1 Integration with Climate-Smart Agriculture**

Biochar fits well within the principles of **climate-smart agriculture (CSA)** by contributing to **resilience, mitigation, and productivity**. Its ability to **sequester carbon**, **reduce greenhouse gas emissions**, and **improve soil health** positions it as a vital tool for adapting to climate variability (Chouhan et al., 2023). Future strategies should emphasize incorporating biochar into CSA frameworks, especially in regions prone to soil degradation, drought, and low fertilizer use efficiency. Combining biochar with drought-resilient crops like mung bean may improve system resilience while enhancing sustainability.

**8.2 Biochar Blends: Compost + Biochar and Nano-Biochar**

One promising area of advancement is the development of **biochar blends** for targeted soil improvement. Co-application of **biochar with compost or farmyard manure** enhances nutrient availability, microbial diversity, and organic matter stability, leveraging the strengths of both materials. Compost-biochar blends can reduce nitrogen immobilization associated with pure biochar and improve overall nutrient cycling. **Nano-biochar**, an innovative form with reduced particle size and enhanced reactivity, is gaining attention for its superior **adsorptive and nutrient-delivery capabilities**. Preliminary findings suggest that nano-biochar improves **root uptake efficiency**, **enzyme activity**, and **plant growth** more rapidly than conventional biochar. However, its long-term ecological effects, potential toxicity, and cost-effectiveness still require thorough investigation.

**8.3 Field Trials on Mung Bean and Other Legumes**

While numerous **pot experiments** have demonstrated the benefits of sugarcane biochar, **field-level trials under diverse agro-climatic conditions** remain limited. There is a critical need for **multi-season, multi-location trials** focusing on mung bean and other legumes (e.g., cowpea, chickpea, pigeon pea) to validate biochar’s agronomic effectiveness. These trials should evaluate: Optimum application rates, Timing and method of application, Crop responses under organic and inorganic nutrient regimes, Long-term changes in soil health and crop productivity. This real-world data is essential for translating laboratory findings into actionable recommendations for farmers.

**8.4 Precision Application Based on Soil and Crop Needs**

As biochar characteristics vary based on **feedstock** and **production conditions**, a "one-size-fits-all" approach is impractical. Future research should focus on developing **site-specific biochar formulations** and **precision application protocols** tailored to **soil texture**, **pH**, **nutrient status**, and **crop requirements**. This approach will enhance efficiency, minimize risks of over-application, and ensure maximum benefit for mung bean cultivation systems. Advances in **soil mapping, remote sensing**, and **decision-support tools** can be harnessed to design **biochar-based precision input strategies** aligned with sustainability goals.

**9. CONCLUSION**

The sustainable management of agricultural waste and the need for enhanced soil health have brought biochar into the spotlight as a multifunctional soil amendment. Among various biomass sources, **sugarcane bagasse** offers immense potential due to its global abundance, favourable chemical composition, and high carbon content. This review comprehensively examined the production processes, physicochemical properties, and agronomic benefits of sugarcane bagasse-derived biochar, with a particular focus on **mung bean** cultivation. Biochar application has been shown to improve key **soil properties** including pH, cation exchange capacity, water-holding capacity, and microbial activity leading to enhanced nutrient availability and reduced nutrient leaching. In mung bean systems, these changes translate to improved **germination**, **root development**, **nodulation**, **biomass accumulation**, and ultimately **higher seed yield**. The integration of biochar with compost or mineral fertilizers further amplifies its effects, while emerging forms like nano-biochar offer new research avenues. Despite its promise, the full-scale adoption of biochar remains limited by knowledge gaps related to **field-level performance**, **economic feasibility**, and **application precision**. Future research should focus on **multi-location field trials**, **site-specific application strategies**, and **life cycle assessments** to validate its long-term viability and sustainability. In conclusion, sugarcane biochar represents a strategic tool for transforming agro-waste into a valuable input for sustainable crop production. When properly managed and contextually applied, it can significantly contribute to **climate-smart agriculture**, improved soil fertility, and enhanced productivity in legume-based systems like mung bean.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing interests

Authors have declared that no competing interests exist.

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