

Review on the Integration of Biochar and Internet of Things (IoT) for Atmospheric Carbon Sequestration

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Abstract. *The continuous increase in atmospheric carbon dioxide is a major factor affecting climate change. Biochar, a product realized from pyrolysis of biomass feed with abundant carbon, has gained researchers' interests for long-term mitigation of greenhouse gases and sequestration of atmospheric carbon. This study reviews recent literature on the properties, production, and biochar's potential in the sequestration of atmospheric carbon. It was reviewed that the application of biochar from rice husk, corn stover, sugarcane bagasse, sawdust, and animal manure to the field at the rates of 10, 12, 15, 8, and 10t/ha, will reduce the emission of greenhouse gases by 20, 50, 40, 18, and 55%, respectively. The current trends of incorporating IoT for the monitoring of real-time soil and climate carbon dynamics were also investigated. The review revealed that the adoption of biochar and IoT technologies provides sustainable, scalable, and transparent approaches to sequestration of atmospheric carbon.*

Keywords: *Biochar, Biomass, Carbon sequestration, Greenhouse Gas.*

1. Introduction

The global environment is faced with climate change problems, affecting ecosystems, livelihoods of humans, and weather patterns. The excess release of atmospheric CO₂ is one of the major contributors to the release of atmospheric greenhouse gases and climate change effects [1]. The emission of these gases is majorly a result of anthropogenic activities, such as combustion of fossil fuel and deforestation [2]. The effects have been serious, with a significant increase in the level of atmospheric CO₂, which has led to global temperature escalation [1]. In 2020, the concentration of world atmospheric



CO₂ peaked at 412 parts per million. If rapid steps to reduce these emissions are not developed and implemented by the year 2030, the concentration of atmospheric CO₂ could increase to alarming levels of 600 to 1500 [3].

The loss of a large amount of soil carbon has been attributed to an increase in atmospheric CO₂ levels [4], posing a serious challenge to the quality and yield of crops [5]. This concern arises due to an increase in population which will lead to increase in the demand for food in the coming years [6]. Moreover, the health consequences of prolonged and frequent exposure to atmospheric CO₂ beyond 1000 ppm were highlighted by recent studies [7]. The impacts of these consequences include reduction in bone mineral density, inflammation, formation of carbon deposits in the kidney, compromised higher-level cognitive functions, impaired endothelial function, and increased oxidative stress [7]. Due to these challenges, it becomes crucial to implement and explore techniques that effectively reduce emission of carbon to reduce atmospheric CO₂ and facilitate long-term sequestration of soil carbon to retain carbon that is stable in the soil. Taking measures that are decisive is crucial to address the negative effects of climate change and secure a future that is sustainable for both the well-being of humans and the natural environment.

Biochar is a solid material that is derived from biomass mainly through a process that is thermochemical under high-temperature and pressure conditions in the absence of oxygen. Recently, biochar was reported as a promising soil mineralizer due to its interaction with soil systems and physicochemical properties that are unique [8]. When added to soils, biochar improves the fertility of the soil, soil water holding capacity, and nutrient retention. Its porous attributes provide a home for microorganisms that are beneficial, promoting the growth of plants, and improving soil health [9]. Furthermore, biochar has high microbial stability and chemical attributes due to its remarkable molecular structure. A significant long-term study conducted over an eight year's period evaluated biochar's decomposition from ryegrass using ¹⁴C compound analysis. The study revealed a slow decomposition rate that is exceptional, with the biochar losing only a carbon content of 7×10⁻⁴% per day under ideal conditions [10]. This signifies that for biochar to lose 1% of its carbon content, it would take nearly 400 years. In another study, the residence time of biochar derived from *Eucalyptus saligna*, pyrolyzed, was assessed at 550°C and subsequently added to soils at 20°C. The study reported remarkable long-term residence time for biochar, with an average residence time range from 732 to 1061 years [11]. These studies validated and established the compelling evidence about the enduring nature of biochar as an effective carbon sink, emphasizing its role as a long-lasting and sustainable solution and alternative for the sequestration of soil carbon.

Despite the potential of biochar gaining researchers' interests for improving soil carbon storage and mitigating climate change effects [12], there is a need to balance the identification of research priorities and the existing knowledge, and fill the understanding

gaps. The objective of this review is to connect the bridge of these knowledge gaps by analyzing the mechanisms, properties, and incorporation of IoT associated with the application of biochar for the sequestration of atmospheric and soil carbon. Despite the potential of biochar to reduce the accumulation of atmospheric carbon dioxide (CO₂) by improving biomass yields, a recent and comprehensive overview of its properties will assist in making decisions, support the establishment of standardized protocols, and guide future research in this field of study. Majorly, the collaborative effort on the adoption and use of biochar for atmospheric carbon sequestration will pave the way for the global fight against climate change. Also, this review considers various fields and guidelines for biochar production as well as the present state of industries in the business of atmospheric carbon removal, it provides guidelines that can assist in the design and development of a commercial biochar production system tailored towards removal of atmospheric carbon. The investigation will cover the techniques involved in the analysis of common feedstock, technologies of production.

2. Production and Characteristics of Biochar

The effectiveness and properties of biochar are connected to the processes and materials used in its production [13]. A proper comprehension of the pyrolysis techniques and feedstocks is crucial to the use of biochar for specific environmental and agricultural applications. The variability in its condition of pyrolysis and nature of raw biomass produces biochars with unique physicochemical properties that determine their potential for sequestration of atmospheric carbon, behavior in soil, and suitability for various uses in agronomic studies.

2.1 Biomass Feedstocks

Biochar can be produced from different feedstocks, broadly categorized into animal manure, forestry by-products, agricultural residues, and municipal organic wastes. The critical determinant for chemical composition, porosity, ash content, elemental ratios (C: N, C: O), and specific surface area of the final biochar product is feed biomass. The residues from agriculture, such as wheat straw, coconut shells, rice husks, sugar bagasse, and corn stover are among the most commonly utilized feedstocks due to their renewable nature, high ligno cellulosic content, and abundance. These residues produce biochars with high carbon contents and low ash, and this favor soil carbon stability for long periods. Wastes from forestry, such as bark, sawdust, wood chips, and tree trimmings, offer a biomass source that is rich in lignin. Biochars produced from materials that are woody generally exhibit structural rigidity, aromaticity, and high surface stability, making them suitable for sequestration of carbon. Manures from animal source such as swine manure, poultry litter, and cow dung, though with reduced carbon abundance, are unique for producing biochars that is nutrient-enriched. These

feedstocks produced biochars with high quantities of potassium, phosphorus, and other micronutrients, making them suitable for soil amendments but less suitable for carbon storage for long period due to lower stability of carbon and higher content of ash. Green waste from municipalities, such as kitchen scraps, yard trimmings, and compostable urban biomass, is another feedstock that is viable while offering management of organic waste, these resources often exhibit composition that is heterogeneous, necessitating feedstock homogenization and pre-treatment for the quality of the biochar to be consistent.

2.2 Pyrolysis Process

The thermochemical decomposition of organic matter in an anaerobic environment is called pyrolysis, leading to the production of biochar (solid), bio-oil (liquid), and non-condensable (syngas). The properties and distribution of these products are significantly affected by pyrolysis type and procedure employed, which are largely defined by heating rate, temperature, and residence time.

2.2.1 Slow pyrolysis

The maximization of biochar yield is commonly achieved by this method. It is usually carried out at a moderate range of temperature from 300°C to 500°C with extended residence time, the process of slow pyrolysis favors the formation of biochar that is stabilized and rich in carbon. The steady volatilization of organic compounds is achieved by prolonged exposure to heat, producing biochar with improved porosity, aromaticity, and a higher carbonization degree.

2.2.2 Fast pyrolysis

This process occurs at a similar temperature range that is relative to the slow pyrolysis process (350°C–600°C) but involves fast rates of heating and short vapor residence times (seconds). The process of fast pyrolysis is primarily designed for bio-oil production, with the secondary product being biochar. Greater heterogeneity and lower stability in terms of composition and structure are the results of biochar produced with the fast pyrolysis method [14].

2.2.3 Gasification

The process of gasification involves heating of biomass at a higher temperature range often greater than 700°C, under limited and controlled aerobic conditions or the introduction of steam to oxidize the biomass partially. The aim of gasification of biomass is to produce syngas (a mixture of CH₄, CO, H₂), the end product, which is biochar, is usually produced in reduced quantities and may have unique physicochemical properties, such as reduced surface functionality and high ash content (15;16).

2.3 Review and Benefits of Different Biochar Sources for Climate Mitigation

Table 1 reveals the conversion of biomass from different feedstocks' sources to biochar, and this has prevailed as a promising approach and amendment for greenhouse gas emission reduction from agricultural soils. The table reveals and compares the effectiveness of five types of biochar, such as rice husk, corn stover, sugarcane bagasse, sawdust, and animal manure in reducing emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) from different types of soil at varying application rates.

2.3.1 Greenhouse Gas Mitigation Potential

Table 1 reveals that different biochar reduces the emission of greenhouse gases differently, the biochar produced from animal manure generated the highest methane (CH₄) reduction potential, achieving a reduction potential of 55% when applied at the rate of 10t/ha.. Similarly, biochar derived from corn stover demonstrated improved efficacy in the mitigation of methane, reducing methane emissions by 50% at the application rate of 12t/ha on sandy soils. These results signify that organic residues produced biochars with high lignin and nutrient content that are majorly effective for the reduction of methane in a soil that is well-drained.

Also, biochar produced from sugarcane bagasse reduced nitrogen oxide (N₂O) emissions by 40% when applied to clay soil at the rate of 15 t/ha. The capacity to retain ammonium and its increased surface area determine the effectiveness of biochar in mitigating the emission of nitrous oxide (N₂O), especially greenhouse gas that is potent, thereby preventing nitrification and denitrification processes in soils that are heavier in nature.

Table 1 also reveal moderate reductions of about 20% and 18% for mitigating carbon dioxide (CO₂) emissions when rice husk and sawdust biochars are used, respectively. A comparable mitigation of carbon dioxide (CO₂) emission was achieved when biochar from rice husk was applied at the rate of 10t/ha to loamy soil and biochar from sawdust was applied at the lower rate of 8t/ha to sandy loam soil. Though, the performance of biochar produced from woody and cellulose-rich biomass for mitigating greenhouse gas emission appear to be low compared to biochars meant for reducing methane and nitrous oxide, their potential for improving soil carbon retention was highlighted in this result.

2.3.2 Soil Type and Application Rate Considerations

The texture of soil determines the effectiveness of biochar application. Loamy soil was reported to have the highest mitigation potential for both methane (CH₄) and carbon IV oxide (CO₂) emissions, whereas the mitigation of nitrogen oxide (N₂O) was better in clay soil. Despite low nutrient and moisture retention of sandy soil,

biochar from corn stover mitigates methane emission effectively in sandy soils, suggesting a possible relationship between soil drainage properties and biochar porosity.

2.3.3 Application Rates

The reduction of greenhouse gas emissions also depends on the application rates of biochar. The higher the application rate of biochar, the higher the reduction in greenhouse gas emission, as reported in Table 1 for corn stover and sugarcane bagasse at application rates of 12 and 15t/ha, respectively. However, this trend was not completely linear, as biochar from animal manure demonstrated the highest mitigation for methane (CH₄) at a moderate application rate of 10 t/ha, this signifies that biochar source and properties may affect its application dosage for reducing greenhouse gas emission in some cases.

Table 1. Biochar's Role in Reducing Greenhouse Gas Emissions from Soil

Biochar Type	Greenhouse Gas	Reduction Emission (%)	Soil Type	Application Rates (t/ha)
Rice husk	CO ₂	20	Loamy soil	10
Cornstover	CH ₄	50	Sandy soil	12
Sugarcane bargass	N ₂ O	40	Clay soil	15
Saw dust	CO ₂	18	Sandy Loam	8
Animal manure	CH ₄	55	Loamy Soil	10

[14]

2.4 Process of Atmospheric Carbon Sequestration by Biochar

The three major techniques for improving climate change effects are negative emissions, conventional emissions, and radioactive. The reduction of emission, nuclear power, fuel switching, efficiency gains, storage technologies, and carbon capture through a renewable energy approach is the focus of conventional emission. The methods for removing atmospheric carbon, such as technological, biogenic, and hybrid carbon sequestration approaches, are the new methods also referred to as negative emissions. This involves soil carbon sequestration, direct air carbon capture and storage, bio-carbon capture and storage by bioenergy, wetland restoration, forestation, biochar, ocean fertilization, enhanced terrestrial weathering, biomass utilization, alkalinity enhancement, and mineral carbonization.

The development of financially and effectively carbon removal projects is crucial due to the present state of emergency in climate issues. Biochar improves atmospheric carbon capturing, utilization, and storage, it has been considered as a negative emissions technology that is promising [17]. The process of photosynthesis that occurs during plant growth assists in achieving the removal of atmospheric carbon

coupled with a conversion process that is thermochemical and results in the formation of a solid carbonaceous material called biochar. Biochar possesses a carbon formation that is very stable and can withstand biological and thermal degradation for a long period of time. The biochar can then be mixed and stored in soils, building various carbon sinks and structures, where its additional benefits can be derived. It is projected that atmospheric carbon removal in the range of 0.3–2 Gt CO₂ year⁻¹ through biochar application will be achieved by 2050 [18].

The potential of carbon sequestration by biochar is remarkably affected by its surface area and particle size. Smaller particle sizes (diameter of less than 0.045 mm) and larger surface areas (exceeding 100 m²/g) offer benefits that are numerous. Initially, the reduction of biochar particle size improves the area of contact between the surrounding environment and biochar, improving the interaction and adsorption of greenhouse gas emissions such as CH₄, CO₂, and N₂O [9]. This increase in surface contact allows for more effective retention and capture of carbon within the biochar structure. A Recent study conducted on biochar produced from different-sized fruit shells of *Camellia oleifera* revealed that the smallest fruit shell sizes, ranging from 0.5 to 2 mm were attributed to the lowest emission rates of CO₂ and N₂O [19]. Larger fruit shell sizes ranging from 2–5 mm or 5–10 mm generally have a surface area-to-volume ratio that is lower, which restricts accessibility to microbes and subsequent degradation. Therefore, biochar particles that are large may exhibit CO₂ efflux reduction due to reduction in the activity of microbes and slower rates of decomposition.

2.5 The Role of IoT for Monitoring Environmental Hazards

As a result of different changes experienced in the environment, the sharing of data and its reuse with the assistance of artificial intelligence instruments and algorithms, play a crucial role in assisting researchers to protect the environment that is continuously threatened and ensure the development of environmental management practices that are sustainable. Scientists can utilize online data platforms and sharing tools that consist intricate and vast environmental and earth science data like, climatic and atmospheric data, hydrology, pedology, ecology, and biodiversity [20] for theories testing, analysis, and interpretation, model prediction and experimental data that lead to better understanding of the environment.

The use of artificial neural networks (ANN) for short- and long-term forecasting applications for air pollution has been adopted. An environmental toxicology model enabled by IoT to detect air pollution was developed [21]. A model was developed to report real-time monitoring of air quality using artificial intelligence with the adoption of a broadcast alarm and cloud server when hazardous pollutants are detected in the air. The artificial algae algorithm (AAA) and Elman neural network (ENN) models predict and classify air quality in future timestamps. The data collected by sensors are sent to a cloud server with the aid of WiFi gateways. The artificial algae

algorithm (AAA) model optimizes the Elman neural network (ENN) model parameters during data processing.

The popularity of unmanned machines and artificial intelligence arises from the real-time and effective automated solutions that these technologies provide when placed in toxic environments. They can discover and isolate potential threats before they cause harm, with reduced or no human involvement [22]. Recent technologies have been developed for the integration of robots that are autonomous with flexible sensors and remotely deployed in toxic and unsafe environments. They can improve neighborhood and workers' safety without any threat to human life. These devices are integrated with systems capable of monitoring, exploring, detecting, and alarming when events that are hazardous occur [23].

2.6 Role of Internet of Things (IoT) for Atmospheric Carbon Sequestration

- i. Real-time data collection.
Internet of things devices, such as soil sensors measure parameters like the levels of soil moisture, soil temperature, and soil organic carbon in real-time. These parameters are crucial for the assessment of the efficiency of carbon sequestration.
- ii. Remote Monitoring
Systems that are enabled with IoT provide carbon data that can be remotely accessed, thereby reducing frequent visitation to the field. This is particularly recommended for commercial agroecosystems where manual monitoring is practically impossible.
- iii. Integration with GIS and Remote Sensing
This involves integration of IoT with remote sensing technologies and Geographic Information Systems (GIS) to provide temporal and spatial analyses of carbon sequestration across different agroecosystems.
- iv. Data-Driven Decision Making
- v. IoT systems enable the analysis of data through machine learning and artificial intelligence algorithms. These approaches assist in the optimization of farm activities, such as cover cropping and crop rotation to maximize the rate of atmospheric carbon sequestration.

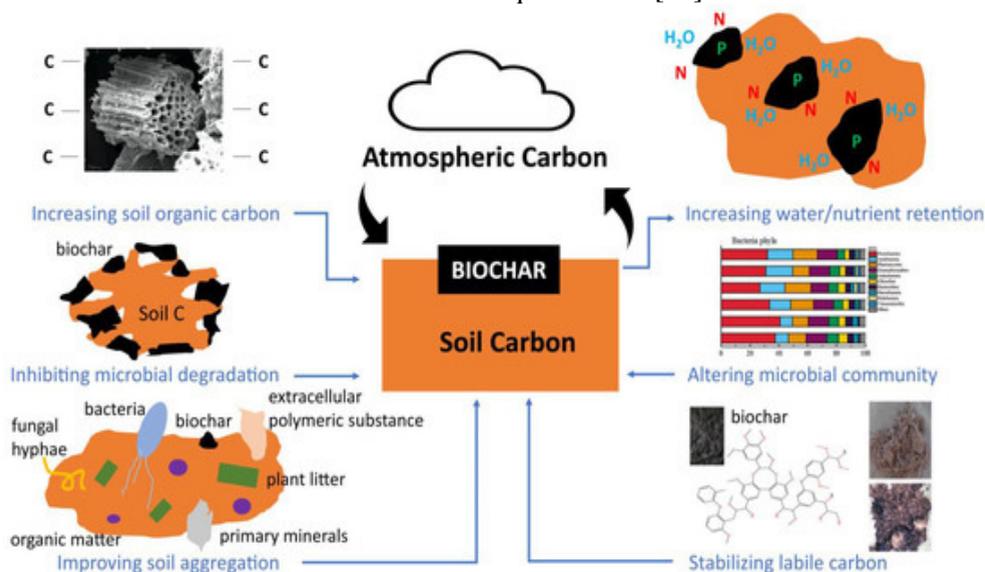
2.7 Applications of IoT in Carbon Sequestration

- i. Precision Agriculture IoT assists in the accurate monitoring of carbon levels in different farm zones, allowing management that is site specific to improve sequestration of carbon.
- ii. Agroforestry Systems IoT tools assist in the monitoring of carbon stocks in the systems of agroforestry by measuring the level of soil carbon, biomass growth, environmental conditions and promoting land-use practices that are sustainable.

- iii. Conservation Tillage Sensors are used to monitor disturbance in soil disturbance and level of organic matter under tillage systems that are conservative, thereby optimizing tillage practices for maximum carbon retention.
- iv. Carbon Credit Certification IoT provides verifiable and accurate data for the market associated with carbon credits, enabling farmers to make money from their efforts on carbon sequestration. This generates sustainable practices that are incentivized.

2.8 Future Prospects

- i. Integration with Artificial Intelligence. Analytics that are artificial intelligence driven will improve applications of IoT by predicting the trend of carbon sequestration and suggesting practices that are adaptive in management.
- ii. Blockchain for Carbon Credit Verification. The technology attributed to blockchain can ensure trust and transparency in carbon credit markets by recording carbon data generated from IoT.
- iii. Advanced Sensors. The development of sensors with high precision and low cost will make IoT systems more efficient for proper carbon monitoring.
- iv. Policy Support Governments and organizations. There is a need to support the adoption of IoT through training, subsidies, and development of infrastructure to scale the efforts on carbon sequestration. [24]



[25]

Fig. 1. Climate benefits of biochar for atmospheric CO₂ removal

3. Conclusion

The monitoring of carbon sequestration through integration with IoT offers an approach that is promising for sustainable agricultural systems and climate change mitigation. By setting up real-time data collection, analysis, and decision-making, IoT technologies improve the effectiveness and efficiency of carbon management practices. However, addressing attributed challenges such as high costs and connectivity issues is crucial to exploring and deriving the full potential of IoT in carbon sequestration.

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