

Review

From Waste to Resource: Evaluating the Impact of Biosolid-Derived Biochar on Agriculture and the Environment

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Abstract: The escalating production of biosolids from wastewater treatment plants presents significant environmental and health challenges due to the presence of pathogens, trace organic pollutants, and heavy metals. Transforming biosolids into biochar through pyrolysis offers a sustainable solution, enhancing soil fertility and mitigating greenhouse gas emissions. This review critically evaluates the pyrolysis processes (slow, fast, and flash) for biosolid conversion and examines the impact of biosolid-derived biochar on soil nutrient retention, crop productivity, and greenhouse gas emissions. Findings from various studies demonstrate that BDB can significantly reduce emissions of N_2O , CH_4 , and CO_2 while improving soil health. However, challenges such as standardizing production methods, addressing heavy metal content, and ensuring economic feasibility must be overcome. Future research should focus on optimizing pyrolysis conditions, developing regulatory frameworks, and conducting comprehensive economic analyses to support the large-scale implementation of BDB in sustainable agriculture.

Keywords: biosolid; biochar; pyrolysis; greenhouse gas mitigation; soil fertility; sustainable agriculture; waste management; carbon sequestration; economic feasibility



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1. Introduction

Municipal wastewater treatment plants (WWTPs) are integral to urban infrastructure, treating sewage and protecting water quality. However, these plants produce a significant byproduct, i.e., sewage sludge. This sludge is laden with pathogens, trace organic pollutants, and heavy metals, making its disposal a challenging task [1]. The transformation of sewage sludge into biosolids through stabilization technologies mitigates environmental and health risks, rendering it suitable for land application and energy recovery [1].

Notably, biosolids are rich in organic and inorganic nutrients vital for plant growth, including nitrogen (N), potassium (K), phosphorus (P), sulfur (S), zinc (Zn), and copper (Cu) [2]. These nutrients can improve soil fertility and support sustainable agricultural practices, underscoring the importance of effective management of biosolids.

However, the generation of biosolids is escalating globally, driven by population growth and urbanization. In 2018, estimates indicated that WWTPs in the USA produced approximately 8 million tons of dry biosolids [3], while those in the European Union and China generated 11.7 million tons and 9.18 million tons, respectively [4]. The global production of biosolids was estimated at 45 million tons [4]. Unfortunately, this trend is expected to continue with the growing human population and the expanding urbanization worldwide, emphasizing an urgent need for sustainable biosolid management solutions.

Meanwhile, the status of biosolid management varies significantly worldwide [1]. Developed countries have made considerable strides in mitigating environmental and health risks associated with biosolid disposal, thanks to advanced technologies and stringent regulations [1]. For instance, countries like Germany and Japan have implemented robust frameworks to ensure safe biosolid utilization [2]. Conversely, many developing nations

struggle with effective biosolid management due to limited financial resources, inadequate infrastructure, and a lack of expertise [1]. South Africa, for example, faces severe challenges in wastewater treatment, leading to water contamination and waterborne diseases [5]. The improper handling of biosolids in such regions can deplete clean water resources, increase freshwater pollution, and negatively impact aquatic biodiversity [5].

Conventional biosolids management practices, including landfilling and incineration, are often unsustainable and economically burdensome [1]. Landfilling poses significant environmental risks, such as groundwater contamination through leachate and the release of methane (CH_4), a potent greenhouse gas (GHG) [2]. Incineration, although effective in reducing biosolid volume, emits harmful gases like nitrous oxide (N_2O) and sulfur dioxide (SO_2), contributing to air pollution and health hazards [2]. Even land application, while beneficial for soil fertility, can introduce potentially toxic elements and emerging contaminants into the soil [2].

On the contrary, the transformation of biosolids into biochar, a stable carbon-rich product obtained from the pyrolysis of organic material, including biosolids, offers a sustainable and cost-effective solution for biosolid management, addressing the environmental and health risks associated with conventional disposal methods [6]. By enhancing soil properties, improving water and nutrient retention [7], increasing crop yields [8], and mitigating GHG emissions [9], BDB presents a viable strategy for sustainable agriculture and environmental protection. As research and technological advancements continue to evolve, the adoption of BDB can play a crucial role in promoting sustainability at the water–energy–food nexus.

The aim of this review article is to provide a comprehensive evaluation of the agricultural applications of BDBs. Specifically, the article seeks to:

1. Explore BDB production: Detail the processes involved in converting biosolids into biochar, including pretreatment and pyrolysis techniques.
2. Evaluate agricultural and environmental benefits: Investigate the potential of BDB to enhance soil properties, improve water and nutrient retention, increase crop yields, and mitigate GHG emissions through a review of recent studies.
3. Identify challenges and future directions: Discuss the barriers to widespread adoption of BDB in agriculture, including social acceptance, the presence of contaminants, and regulatory issues, and propose future research and policy directions to address these challenges and promote sustainable practices.

By achieving these objectives, the review aims to provide a detailed understanding of the viability and benefits of using BDB in agriculture, contributing to the development of sustainable biosolid management strategies and enhanced agricultural productivity.

2. Production of Biochar from Biosolids

2.1. Pretreatment of Biosolids

Biosolids undergo essential pretreatment processes, including dewatering and drying, before they can be effectively converted into biochar through pyrolysis [6]. These pretreatment steps are crucial for reducing the moisture content of biosolids, enhancing their energy efficiency during pyrolysis, and improving the quality of the resulting biochar [6]. The primary dewatering techniques used are centrifugation, filter presses, and electro-dewatering, each selected based on various economic, environmental, and regulatory factors [10].

2.1.1. Dewatering Process

The dewatering process is designed to reduce the water content of biosolids, transforming them from a slurry-like state to a more solid form. This step is vital for lowering the energy requirements of subsequent drying and pyrolysis processes [10]. The most commonly used technologies for biosolid dewatering include centrifugation, filter presses, and electro-dewatering [10].

1. **Centrifugation:** Centrifugation is a widely used method for dewatering biosolids, particularly in large-scale wastewater treatment plants [11]. This technique employs centrifugal force to separate water from solid particles. The biosolids are placed in a rotating drum or bowl, which spins at high speeds. The centrifugal force pushes the heavier solid particles outward against the drum wall, while the water moves inward and is removed through a central outlet [11].
2. **Filter presses:** Filter presses use mechanical pressure to dewater biosolids by compressing them between filter plates [12]. This method involves pumping the biosolid slurry into the press, where it is forced between cloth filters under high pressure. The water is squeezed out through the filter cloth, leaving behind a cake of dewatered biosolids [12].
3. **Electro-dewatering:** Electro-dewatering is an advanced method that enhances traditional dewatering techniques by applying an electric field [13]. This process involves placing biosolids between electrodes and applying a direct current. The electric field induces the movement of water towards the electrodes, enhancing the dewatering efficiency [13].

A summary and comparison of the advantages and disadvantages of the above dewatering technologies can be found in Table 1.

Table 1. Comparison of centrifugation, filter presses, and electro-dewatering.

	Centrifugation	Filter Presses	Electro-Dewatering
Mechanism	Use centrifugal force to separate water from solid particles.	Use mechanical pressure to compress biosolids between filter plates.	Use a direct current to induce the movement of water towards the electrodes.
Advantages	(1) Effective for high-throughput operations. (2) Can achieve significant reductions in water content. (3) Relatively fast. (4) Can be automated, thus suitable for continuous operation.	(1) Can achieve high levels of dewatering and achieve a relatively dry cake. (2) Versatile and can handle a wide range of biosolid types.	(1) Can achieve higher dewatering rates and lower residual moisture content compared to conventional methods. (2) Particularly effective for biosolids with high initial moisture content.
Disadvantages	(1) High initial capital costs. (2) Can consume considerable energy. (3) May not be effective for biosolids with very high moisture content.	(1) Batch-based processes can limit throughput compared to continuous methods. (2) Equipment can be bulky, requiring significant space.	(1) It is a relatively new technology and can be costly. (2) Careful control of the electric field is required for the process to prevent overheating and ensure uniform dewatering.

2.1.2. Drying Process

Following dewatering, biosolids typically undergo a drying process to further reduce their moisture content, preparing them for efficient pyrolysis [6]. Several drying methods are employed, including biodrying, solar drying, and thermal drying [14].

1. **Biodrying:** Biodrying leverages microbial activity to reduce moisture content in biosolids [15]. During this process, microorganisms decompose organic matter, generating heat that evaporates the water. The biosolids are aerated to support microbial activity and facilitate moisture removal [15].
2. **Solar drying:** Solar drying utilizes solar energy to evaporate water from biosolids [4]. This method involves spreading the dewatered biosolids on drying beds or platforms exposed to sunlight. Solar radiation heats the biosolids, causing moisture to evaporate [4].
3. **Thermal drying:** Thermal drying applies external heat to reduce the moisture content of biosolids [16]. This process can be conducted using various systems, including rotary dryers, belt dryers, and fluidized bed dryers [16]. Thermal drying is effective in achieving very low moisture levels [16].

A summary and comparison of the advantages and disadvantages of the above dewatering technologies can be found in Table 2.

Table 2. Comparison of biodrying, solar drying, and thermal drying.

	Biodrying	Solar Drying	Thermal Drying
Mechanism	Use heat generated from the decomposition of organic matter by microorganisms.	Use heat from solar radiation.	Use a direct current to induce the movement of water towards the electrodes.
Advantages	(1) An environmentally friendly process. (2) Can reduce the need for external heat sources. (3) Can enhance the stabilization of biosolids by reducing pathogen levels.	(1) Can achieve high levels of dewatering and achieve a relatively dry case. (2) Versatile and can handle a wide range of biosolid types.	(1) Can achieve higher dewatering rates and lower residual moisture content compared to conventional methods. (2) Particularly effective for biosolids with high initial moisture content.
Disadvantages	(1) A slow process that may require several weeks to achieve the desired moisture reduction. (2) Performance depends on microbial activities, which can be influenced by external factors such as temperature and aeration.	(1) Batch-based processes can limit throughput compared to continuous methods. (2) Equipment can be bulky, requiring significant space.	(1) It is a relatively new technology and can be costly. (2) Careful control of the electric field is required for the process to prevent overheating and ensure uniform dewatering.

2.1.3. Integration and Optimization of Dewatering and Drying

The choice of dewatering and drying methods is influenced by factors such as the initial moisture content of the biosolids, available resources, regulatory requirements, and environmental considerations. Integrating dewatering and drying processes can optimize the overall efficiency and effectiveness of biosolid pretreatment [10].

Some advanced systems combine mechanical dewatering and drying processes to maximize efficiency. For example, a combined centrifugation and thermal drying system can first use centrifugation to achieve substantial moisture reduction, followed by thermal drying to achieve the desired dryness [17]. This approach can optimize energy use and reduce overall processing time [17].

Economic feasibility is a critical factor in selecting dewatering and drying methods. While advanced techniques like electro-dewatering and thermal drying offer high efficiency, they also entail higher capital and operational costs [13]. Conversely, methods like solar drying and biodrying are more cost-effective but may require longer processing times and a larger space [4,15].

Environmental impact is another crucial consideration. Processes that generate emissions or consume significant energy need to be balanced with the benefits of reduced biosolid volume and improved stabilization. Renewable energy sources and energy-efficient technologies can help mitigate the environmental footprint of these processes.

The final decision about dewatering and drying methods depends on a careful assessment of economic, environmental, and regulatory factors. By optimizing these pretreatment processes, the efficiency of biosolid-to-biochar conversion can be enhanced, paving the way for sustainable biosolid management and agricultural applications.

2.2. Pyrolysis of Biosolids

Pyrolysis is a thermochemical decomposition process that occurs in the absence of oxygen, transforming organic materials, such as biosolids, into biochar, syngas, and bio-oil [18]. The efficiency and characteristics of the resulting biochar are highly dependent on the pyrolysis conditions, which can be broadly categorized into slow, fast, and flash pyrolysis [19]. Each type of pyrolysis varies in terms of temperature, heating rate, and residence time, significantly affecting the properties and potential applications of the biochar produced [19].

2.2.1. Slow Pyrolysis

Slow pyrolysis is characterized by its relatively low temperatures and long residence times. Typically conducted at temperatures ranging from 350 to 550 °C with a heating rate of 0.1–1.0 °C/s, this process has a residence time of 5–30 min. The primary product of slow pyrolysis is biochar, which contains a high carbon content, making it particularly valuable for soil amendment applications [20].

The slow pyrolysis process maximizes the yield of solid biochar while minimizing the production of liquids and gases [20]. This type of pyrolysis is advantageous for producing biochar with stable carbon structures that are resistant to decomposition, thereby enhancing its effectiveness for long-term soil carbon sequestration [21]. The high carbon content also improves soil fertility by increasing cation exchange capacity (CEC), water retention, and microbial activity [19].

Recent studies have demonstrated the benefits of slow-pyrolysis biochar in agriculture. For example, biochar produced from sewage sludge through slow pyrolysis has been shown to improve soil nutrient retention and reduce the need for chemical fertilizers, thereby promoting sustainable farming practices [22]. Additionally, the porous nature of biochar enhances soil aeration and water infiltration, which are critical for healthy plant growth [23].

2.2.2. Fast Pyrolysis

Fast pyrolysis involves rapid heating to high temperatures, typically between 800 and 1300 °C, with heating rates of 10–200 °C/s and residence times of 1–10 s [20]. The primary products of fast pyrolysis are bio-oil and syngas, with biochar being a secondary byproduct [24]. The high temperatures and short residence times favor the production of liquid and gaseous products over solid biochar [24].

Biochar produced through fast pyrolysis tends to have different properties compared to slow-pyrolysis biochar [19]. It often has a lower carbon content and a higher ash content, which can affect its suitability for certain soil applications [19]. However, fast-pyrolysis biochar can still enhance soil properties, particularly in terms of nutrient availability and soil structure improvement [19].

The production of bio-oil and syngas during fast pyrolysis offers additional benefits. Bio-oil can be used as a renewable fuel or chemical feedstock, while syngas can be utilized for energy generation [24]. This makes fast pyrolysis a versatile process that can contribute to both waste management and energy production.

2.2.3. Flash Pyrolysis

Flash pyrolysis is distinguished by its extremely high heat transfer rates and very short vapor phase residence times, typically 0.5–1.0 s, with processing temperatures around 500–550 °C [20]. This rapid process aims to maximize the yield of bio-oil while producing biochar as a secondary product [20].

The biochar produced by flash pyrolysis generally has unique characteristics, such as a higher surface area and porosity compared to biochar from slower processes. These properties can enhance its effectiveness as a soil amendment, particularly for improving water retention and providing a habitat for beneficial soil microorganisms [25].

Flash pyrolysis is particularly suitable for applications where rapid processing and high yields of liquid products are desired. The high surface area of flash pyrolysis biochar also makes it suitable for applications beyond agriculture, such as in water filtration and pollution remediation [25].

A comprehensive comparison of the three pyrolysis processes is summarized in Table 3, highlighting their unique characteristics and applications.

Table 3. Comparison of slow, fast, and flash pyrolysis.

	Slow Pyrolysis	Fast Pyrolysis	Flash Pyrolysis
Temperature Range	350–550 °C	800–1300 °C	500–550 °C
Heating Rate	0.1–1.0 °C/s	10–200 °C/s	High heat transfer rates
Residence Time	5–30 min	1–10 s	0.5–1.0 s
Main Product	Biochar	Bio-oil and syngas	Bio-oil
Secondary Products	Syngas and bio-oil	Biochar	Biochar and syngas
Biochar Yield	High	Moderate	Low
Bio-oil Yield	Low	High	High
Syngas Yield	Moderate	Moderate	Moderate
Carbon Content	High	Lower than slow pyrolysis	Moderate
Surface Area	Lower than flash pyrolysis	Lower than flash pyrolysis	High
Porosity	Moderate	Lower than flash pyrolysis	High
Energy Efficiency	Moderate to high	Moderate	High
Complexity	Low to moderate	High	Very high
Cost	Moderate	High	Very high
Suitability	Soil amendment, carbon sequestration	Energy production, chemical feedstocks	Rapid processing, high-value products
Advantages	(1) Produces stable biochar with a high carbon content. (2) Enhances soil fertility. (3) Increases soil cation exchange capacity.	(1) High yields of bio-oil and syngas. (2) Versatile for energy production.	(1) High-surface-area biochar. (2) Effective for rapid processing and high-value applications.
Disadvantages	(1) Lower processing time. (2) Lower yields of bio-oil and syngas.	(1) Requires complex and costly equipment. (2) Biochar with lower stability.	(1) Very short residence time. (2) Requires highly controlled conditions. (3) Lower biochar yield.

3. Effects of Biosolid-Derived Biochar Applications

3.1. Enhanced Water Holding with the Application of Biosolid-Derived Biochar

3.1.1. Mechanisms for Enhancing Soil Water Holding Capacity

The application of BDBs has gained considerable attention in recent years due to its potential to enhance soil properties, particularly soil water holding capacity (WHC). Soil WHC is a critical factor for agricultural productivity, influencing water availability for plants and overall soil health. BDB application can significantly improve the WHC of soils through various mechanisms, including enhancing soil structure, increasing porosity, and improving water retention properties.

Improved Soil Structure: BDB can promote soil aggregation by binding soil particles together [25]. This aggregation creates larger pore spaces, which are essential for water infiltration and storage. Studies have shown that the addition of biochar to sandy soils can improve soil aggregation, leading to enhanced water retention [26]. Moreover, BDB can reduce soil compaction, particularly in heavy clay soils [27]. By improving soil structure and reducing bulk density, BDB creates more pore spaces, which can hold more water and make it available to plants [27].

Increased Porosity: Biochar's porous nature contributes to the development of both micro- and macro-pores within the soil matrix [28]. Micro-pores are crucial for holding water against gravitational forces, while macro-pores facilitate water infiltration and aeration [29]. The high porosity of BDB has been documented to increase soil WHC significantly [30]. Furthermore, BDB has a high specific surface area, providing numerous sites for water adsorption. This characteristic is particularly beneficial in arid and semi-arid regions where water retention is a critical concern [31].

Enhanced Water Retention: BDB contains various hydrophilic functional groups on its surface, which can attract and retain water molecules. This increases the ability of soil to hold water, even under drought conditions [30]. Furthermore, research has shown that biochar application can increase soil moisture content by 15–30%, depending on soil type and biochar properties [32,33]. This is particularly beneficial for crops during dry spells, reducing the need for irrigation [34].

3.1.2. Empirical Evidence for Enhanced Water Holding from Previous Studies

Numerous studies have provided empirical evidence supporting the positive effects of BDB on soil WHC. For example, Razzaghi et al. (2020) investigated the impact of biochar derived from various feedstocks, including biosolids, on sandy loam and clay loam soils [7]. The results indicated that BDB significantly increased the WHC of both soil types, with improvements of up to 20% in sandy loam and 15% in clay loam soils [7]. The increased WHC was attributed to enhanced soil aggregation and increased porosity [30].

A meta-analysis by Wei et al. (2023) reviewed multiple studies on biochar application, including BDB, and its effects on soil properties [35]. The analysis concluded that biochar application consistently improves soil WHC across various soil types and climates. The WHC improvements ranged from 10% to 50%, highlighting the versatility of biochar in different agricultural settings [35].

Field trials conducted in tropical regions with highly weathered soils demonstrated that BDB application significantly increased soil WHC, which resulted in improved crop yields [36]. The study reported a 25% increase in WHC and a corresponding 20% increase in maize yield. The biochar was particularly effective in retaining moisture during dry periods, thus enhancing plant growth [36]. Similarly, Heiskanen et al. (2022) studied the effects of BDB on the WHC of sandy soils under greenhouse conditions [37]. The results showed that BDB application improved the soil's water retention capacity by 25–35%. The study also observed that the enhanced WHC led to reduced water stress in plants, promoting better growth and development [37].

3.2. Improved Nutrient Retention with the Application of Biosolid-Derived Biochar

3.2.1. Mechanisms for Improving Soil Nutrient Retention

Biosolid-derived biochar is increasingly recognized for its potential to enhance soil nutrient retention and improve overall soil fertility. The application of BDB to agricultural soils can have significant positive effects on nutrient availability, soil structure, microbial activity, and plant growth. Numerous studies have investigated these impacts, providing insights into the mechanisms by which BDB influences soil nutrient dynamics and the associated benefits for crop productivity.

Added Nutrient Availability: BDB is rich in essential nutrients such as N, P, K, S, Zn, and Cu, which are crucial for plant growth [34]. The pyrolysis process concentrates these nutrients in the biochar, making them more readily available to plants when applied to soil [38]. This nutrient concentration effect can significantly enhance soil fertility, particularly in nutrient-poor soils [39].

Improved Soil Structure: As previously discussed, the application of BDB can improve soil physical properties, such as soil structure and water retention capacity. The porous nature of biochar increases soil aeration and enhances the ability of soil to retain water, which is particularly beneficial in drought-prone areas [40]. Additionally, BDB contributes to soil aggregation by binding soil particles together, which improves soil structure and reduces erosion [41]. This aggregation effect enhances root penetration and water infiltration, leading to better plant growth [42]. Studies have shown that soils amended with BDB have higher aggregate stability, which is crucial for maintaining soil health and productivity [42].

Enhanced Water Holding Capacity: The high porosity of BDB allows it to act as a sponge, holding significant amounts of water and slowly releasing it to plants [30]. This water-holding capacity can reduce the need for irrigation, making agriculture more sustainable, especially in water-scarce regions [40]. For example, Karhu et al. (2021) reported that soils amended with BDB retained more water and exhibited reduced water stress in plants, leading to higher crop yields during dry periods [43].

Increased Microbial Activity: BDB can positively influence soil microbial activity and diversity, which are essential for nutrient cycling and soil health [44]. Biochar provides a habitat for beneficial soil microorganisms, including bacteria and fungi, that play critical roles in decomposing organic matter and releasing nutrients [44]. Studies have shown that BDB application increases microbial biomass and activity in soils. This enhanced microbial

activity accelerates the decomposition of organic matter and the mineralization of nutrients, making them more available to plants [45]. Moreover, the presence of biochar can stimulate the growth of beneficial microorganisms that suppress soil-borne pathogens, leading to healthier crops [45]. Furthermore, BDB can also promote symbiotic relationships between plants and mycorrhizal fungi [46]. Mycorrhizal fungi form associations with plant roots, extending their hyphae into the soil and increasing the surface area for nutrient absorption. Biochar provides a conducive environment for these fungi, enhancing nutrient uptake and improving plant resilience to environmental stresses [46].

3.2.2. Empirical Evidence for Improved Nutrient Retention from Previous Studies

Studies have shown that BDB can improve nutrient retention in soils through several mechanisms. The porous structure of biochar provides a habitat for N-fixing bacteria, enhancing biological N fixation [47]. Additionally, biochar's high cation exchange capacity (CEC) helps retain ammonium ions (NH_4^+), phosphate ions (PO_4^{3-}), and potassium ions (K^+) in the soil, reducing losses through leaching, runoff, and/or volatilization losses [48,49]. Zwetsloot et al. (2016) found that BDB application to acidic soils increased P availability by reducing P fixation, which is common in such soils [50]. Micronutrients like zinc and copper, which are often deficient in agricultural soils, can also be supplied through BDB applications [51]. Biochar's ability to chelate these micronutrients prevents them from becoming insoluble and unavailable to plants [51]. As a result, crops grown in soils amended with BDB often exhibit improved micronutrient uptake and better overall health [52].

Table 4 presents more examples from studies conducted worldwide. Chagas et al. (2021) reported an 18% increase in N retention with biochar produced at both 300 °C and 500 °C for 30 min [53]. This consistency suggests that N retention is less sensitive to slight variations in pyrolysis temperature within this range. Notably, a slight increase in K retention at 500 °C (0.6%) and a decrease at 300 °C (−11%) were observed [53], indicating that lower pyrolysis temperatures might not be as effective for K retention. The study by Yue et al. (2017) indicated dramatic increases in N, P, and K retention with increasing application rates of biochar produced at 500 °C for 120 min, from 148% (N), 563% (P), and 39% (K) at a 1% application rate to 1409% (N), 2150% (P), and 198% (K) at a 10% application rate, respectively [54]. This significant rise illustrates the dose-dependent effect of BDB on nutrient retention.

Table 4. Effects of the application of different biosolid-derived biochars on the retention of N, P, and K at various application rates.

Origin (City/Country)	Pyrolysis Temperature (°C)	Pyrolysis Time (min)	Application Rate of Biochar (% w/w)	N Retention (% Increase)	P Retention (%) Increase)	K Retention (% Increase)	Ref.
Brasília, Distrito Federal, Brazil	300	30		18%	600%	−11%	[53]
	500	30		18%	585%	0.6%	
	500	120	1%	148%	563%	39%	
Beijing, China	500	120	5%	709%	1567%	114%	[54]
	500	120	10%	1409%	2150%	198%	
Guangzhou, China	700	180	1%	-	-	23%	[55]
	300	180		-	−21%	158,165%	
Uttar Pradesh, India	500	180		-	−80%	17,467%	[56]
	600	180		-	−81%	13,599%	
	300	15	0.5%	-	65%	-	
Poland	300	15	1%	-	124%	-	[57]
	300	15	2%	-	297%	-	

Remarkably, the geographical origin of biosolids and the specific conditions of the pyrolysis process (temperature and time) significantly influence the nutrient retention capabilities of BDB (Table 4). Generally, higher pyrolysis temperatures (500 °C and above) tend to improve nutrient retention, especially for nitrogen and potassium. However, the effects on phosphorus retention can be inconsistent, as seen in the data from India [56]. Moreover, longer pyrolysis times (e.g., 120–180 min) appear to enhance nutrient retention,

likely due to more complete carbonization and stabilization of the biochar [19]. Additionally, higher application rates of BDB consistently result in better nutrient retention, emphasizing the importance of optimizing application rates for specific agricultural practices [54,55,57].

3.3. Increased Crop Production with the Application of Biosolids-Derived Biochar

3.3.1. Mechanisms for Increasing Crop Production

BDB has shown significant potential for enhancing crop production due to its unique properties that improve soil quality and nutrient availability [58,59]. The mechanisms through which BDB impacts crop production include enhancing soil structure, increasing nutrient retention, improving water holding capacity, and promoting beneficial microbial activity [60]. The following sections provide a detailed discussion of these mechanisms and the effects observed in various studies.

Improved Soil Structure: BDB improves soil structure by increasing soil porosity and aggregation [60]. The biochar particles create a more friable soil texture, which enhances root penetration and growth. Improved soil structure also facilitates better aeration and drainage, which are crucial for root respiration and reducing waterlogging conditions that can harm crops [56].

Enhanced Nutrient Retention and Availability: BDB has a high CEC, which allows it to retain essential nutrients like N, P, and K and release them slowly to plants [23]. This reduces nutrient leaching and ensures a steady supply of nutrients over the growing season [42]. Additionally, the porous structure of BDB can adsorb nutrients and make them available to plants, enhancing nutrient use efficiency [38].

Increased Water Holding Capacity: The porous nature of BDB increases the water holding capacity of soil [61]. This is particularly beneficial in arid and semi-arid regions where water scarcity is a major constraint on crop production. Improved water retention reduces the frequency of irrigation and helps maintain soil moisture during dry periods, thereby supporting plant growth and development [34].

Ameliorated Beneficial Microbial Activity: BDB provides a habitat for beneficial soil microorganisms that play a crucial role in nutrient cycling and plant health [29]. The surface area and porosity of biochar offer sites for microbial colonization, enhancing microbial biomass and activity [56]. This, in turn, improves soil fertility and plant resilience to pests and diseases.

3.3.2. Empirical Evidence for Increased Crop Production from Previous Studies

Numerous studies have demonstrated the positive effects of BDB on crop yields. Table 5 below provides a summary of these studies, highlighting the variations in pyrolysis conditions, application rates, crop types, and yield increases observed.

Table 5. Effects of the application of different biosolid-derived biochars on the yields of different crops at various application rates.

Origin (City/Country)	Pyrolysis Temperature (°C)	Pyrolysis Time (min)	Application Rate of Biochar (% w/w)	Crop Type	Yield Increase (%)	Duration of Experiment	Ref.
Brasília, Distrito Federal, Brazil	300	150	-	Corn	58%	5 years	[53]
Brasília, Distrito Federal, Brazil	500	230	-	Corn	47%	5 years	
Brasília, Distrito Federal, Brazil	300	60	-	Corn	50%	2 years	[58]
Brasília, Distrito Federal, Brazil	500	75	-	Corn	54%	2 years	
North China Plain	700–850	240	-	Peanuts	60.43%	2 years	[62]
	300	660	1%	Mungbean	−31%	3 months	[63]
	300	660	2%	Mungbean	49%	3 months	
Delaware, USA	300	660	1%	Winter Wheat	23%	3 months	
	300	660	2%	Winter Wheat	118%	3 months	
	300	660	1%	Spinach	21%	3 months	
	300	660	2%	Spinach	150%	3 months	

The studies conducted in Brasília, Brazil, applied BDB produced at pyrolysis temperatures of 300 °C and 500 °C with varying pyrolysis times. Corn yields increased significantly, with a 58% yield increase at 300 °C over 5 years and a 47% increase at 500 °C over the same period [53]. In a shorter 2-year study, corn yield increases were also notable, with a 50% increase at 300 °C and a 54% increase at 500 °C [58]. The sustained yield improvements over multiple years suggest that BDB provides long-term benefits to soil fertility and structure. The higher yield increases at lower temperatures may be due to better preservation of nutrient content in the biochar, which enhances soil nutrient availability [19].

In the North China Plain, BDB produced at higher temperatures (700–850 °C) was applied to peanut crops. A significant yield increase of 60.43% was observed over a 2-year period [62]. The high pyrolysis temperatures likely resulted in biochar with a high surface area and porosity, enhancing soil water retention and nutrient adsorption [19]. These properties are particularly beneficial in the North China Plain, where soil moisture conservation is crucial [64].

Studies in Delaware, USA, applied BDB at a pyrolysis temperature of 300 °C for 660 min at application rates of 1% and 2% *w/w* to different crops, including mungbean, winter wheat, and spinach [63]. Yield increases varied significantly with the application rate. For mungbean, a 1% application rate resulted in a 31% yield decrease, while a 2% rate increased yield by 49%. Winter wheat showed a 23% increase at 1% and an impressive 118% increase at 2%. Spinach yields increased by 21% at 1% and 150% at 2% [63]. The variability in results suggests that the optimal application rate of BDB is crop-specific. The negative impact on mungbean at the lower rate could be due to initial soil nutrient imbalances or phytotoxicity from incomplete biochar maturation [65]. However, higher application rates generally showed positive effects, indicating that sufficient biochar amendment can significantly enhance soil properties and crop yields. The substantial yield increase in winter wheat and spinach at higher application rates highlights the potential of BDB to support high-demand crops through improved soil fertility and moisture retention.

3.4. Mitigating Greenhouse Gas Emissions with the Application of Biosolids-Derived Biochar

3.4.1. Mechanisms for Mitigating Greenhouse Gas (GHG) Emissions

Greenhouse gas (GHG) emissions, including N₂O, CH₄, and CO₂, are significant contributors to climate change. The application of BDB to soil has been shown to mitigate these emissions through various mechanisms.

Mitigation of N₂O Emission: Biochar can affect soil microbial activity, particularly the processes of nitrification and denitrification, which are responsible for N₂O emissions. Biochar's porous structure provides a habitat for soil microbes, facilitating aerobic conditions that favor nitrification while inhibiting denitrification, thereby reducing N₂O emissions [9]. Moreover, biochar can adsorb NH₄⁺ and NO₃⁻, preventing their leaching and making them less available for denitrification processes that produce N₂O [47]. Moreover, the alkaline nature of biochar can increase soil pH, which tends to suppress the activity of denitrifying bacteria that produce N₂O [19].

Mitigation of CH₄ Emission: The porous nature of biochar enhances soil aeration, reducing anaerobic conditions that favor methanogenesis [9], the microbial process that produces CH₄. Additionally, biochar can influence the composition of soil microbial communities, promoting methanotrophic bacteria that oxidize CH₄ into CO₂, thus reducing net CH₄ emissions [62].

Mitigation of CO₂ Emission: Biochar is highly recalcitrant and can remain in the soil for centuries, acting as a stable carbon sink and reducing the amount of CO₂ released into the atmosphere [21]. Furthermore, the application of biochar can improve soil fertility and plant growth, leading to greater photosynthetic CO₂ uptake by plants [39].

3.4.2. Empirical Evidence for Increased Crop Production from Previous Studies

As previously discussed, the ability of biochar to sequester carbon and its impact on soil microbial activity reduce GHG emissions (Table 6). The stable carbon in biochar

prevents decomposition and subsequent CO₂ release, while changes in soil chemistry reduce N₂O and CH₄ emissions. Grutmacher et al. (2018) conducted a study where biosolid-derived biochar produced at 400 °C for 40 min was applied to soil. The results showed an 87% reduction in N₂O emissions [66], demonstrating the significant impact of BDB on mitigating N₂O emissions in tropical soils.

Table 6. Effects of the application of different biosolid-derived biochars on the emissions of different GHGs at various application rates.

Origin (City/Country)	Pyrolysis Temperature (°C)	Pyrolysis Time (min)	Application Rate of Biochar (% w/w)	N ₂ O (% Change)	CH ₄ (% Change)	CO ₂ (% Change)	Ref.
Campinas, Brazil	400	40	-	−87%	-	-	[66]
Xiamen, China	550	360	5%	−96%	−87%	-	[67]
	550	360	10%	−98%	−81%	-	
Madrid, Spain	400	120	1%	-	-	−11%	[68]
	600	120	1%	-	-	−32%	

In a study by Khan et al. (2013), biochar produced at 550 °C for 360 min was applied at rates of 5% and 10% (*w/w*). The N₂O emissions were reduced by 96% and 98%, respectively [67]. These results highlight the effectiveness of higher biochar application rates in significantly reducing N₂O emissions. The same study also reported substantial reductions in CH₄ emissions by 87% and 81% at 5% and 10% application rates, respectively [67]. This demonstrates the potential of BDB in mitigating CH₄ emissions in paddy soils, which are typically high CH₄ emitters. The substantial decreases in both N₂O and CH₄ emissions highlight the dual benefits of biochar in simultaneously mitigating the emissions of the two GHGs in paddy fields.

Moreover, Méndez et al. (2013) investigated the impact of BDB on CO₂ emissions with biochar produced at 400 °C and 600 °C for 120 min. Application rates of 1% (*w/w*) resulted in CO₂ emission reductions of 11% and 32%, respectively [68]. These findings suggest that higher pyrolysis temperatures can enhance the CO₂ mitigation potential of biochar. Notably, CO₂ emission reductions are less pronounced but still significant. The lower emissions of CO₂ can be explained by the stabilization of carbon within the biochar matrix [69], making it less prone to microbial decomposition. Moreover, biochar can improve plant growth and photosynthesis [54,56], indirectly contributing to CO₂ sequestration.

4. Challenges and Future Perspectives

4.1. Social Acceptance

4.1.1. Issues and Barriers to Social Acceptance

Public acceptance of BDB in agriculture is limited. There is a prevalent fear that biosolids may contain harmful pathogens, heavy metals, and trace organic pollutants, which could pose health risks if used in agriculture. Public skepticism often stems from doubts about the effectiveness of regulatory standards and treatment processes in eliminating these risks [70]. Moreover, the idea of using products derived from human waste can be unappealing to consumers, particularly in cultures where there is a strong aversion to human excreta. There is a perception that food produced using biosolids may be of lower quality or less safe than food produced using conventional fertilizers [70].

Meanwhile, many farmers and consumers are not aware of the benefits of BDB, including its potential to improve soil health, increase crop yields, and mitigate greenhouse gas emissions. Misunderstandings about the pyrolysis process and the transformation of biosolids into biochar contribute to resistance. People may not understand how the process effectively eliminates pathogens and stabilizes contaminants.

4.1.2. Future Directions for Improving Public Acceptance

Public education campaigns have been essential in promoting the use of biosolids in agriculture. For example, the City of Campinas in Brazil has implemented extensive public outreach to demonstrate the safety and benefits of biosolid use, resulting in increased acceptance and use among local farmers [66]. Organizing workshops and training sessions for farmers can provide hands-on experience and knowledge about the benefits and safe use of BDB. These programs should include demonstrations of the pyrolysis process and its effectiveness in eliminating pathogens and stabilizing contaminants. Partnering with agricultural extension services to disseminate information and provide support to farmers can facilitate the adoption of BDB. These services can act as trusted intermediaries, bridging the gap between researchers and farmers.

Additionally, governments can offer financial incentives, such as subsidies or tax breaks, to farmers who adopt BDB. This can help offset initial costs and reduce perceived financial risks. Moreover, establishing and enforcing clear regulatory standards for the production and use of BDB can also help alleviate safety concerns. Providing certifications for BDB products can assure farmers and consumers of their quality and safety.

Furthermore, utilizing various media platforms, including social media, television, and radio, to share success stories and scientific evidence supporting the benefits of BDB can reach a wider audience. Creating engaging content, such as documentaries or short videos, can effectively communicate complex scientific concepts in an accessible manner. Engaging local influencers and community leaders to endorse and promote BDB can help shift public perception. These figures often have a significant influence and can help normalize the use of BDB in agriculture.

Lastly, continued research into the long-term impacts of BDB on soil health, crop yields, and environmental sustainability can provide valuable data to support public acceptance. Publishing these findings in accessible formats and venues can help keep the public informed and engaged. Exploring innovative applications of BDB, such as its use in urban agriculture or community gardens, can demonstrate its versatility and benefits in various contexts, further enhancing public acceptance.

4.2. Possible Toxic Effects

4.2.1. Issues and Barriers with Possible Toxic Effects

While BDB offers numerous benefits for soil amendment and GHG emission mitigation, one significant concern is the potential presence of heavy metals. Heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) can be retained in biochar during the pyrolysis process, posing risks to human health and the environment [71].

Heavy metals in BDB can become bioavailable in the soil, leading to their uptake by plants. When crops grown on soils amended with contaminated biochar are consumed, these metals can enter the human food chain, posing serious health risks [72]. For instance, Cd and Pb are known to cause kidney damage and neurological disorders, respectively [73]. Moreover, heavy metals can negatively affect soil health by disrupting microbial communities and enzyme activities essential for nutrient cycling [74]. This disruption can lead to reduced soil fertility and productivity.

Moreover, heavy metals in their mobile forms can leach from biochar into the soil and groundwater, contaminating water supplies [72]. Chronic exposure to contaminated water can lead to various health issues, including cancer and developmental disorders. When heavy metals leach into water bodies, they can accumulate in aquatic organisms, leading to bioaccumulation and biomagnification in the food web [67]. This can harm fish, birds, and other wildlife, affecting biodiversity and ecosystem stability.

4.2.2. Future Directions for Eliminating Possible Toxic Effects

Various treatment methods and technologies have been investigated and implemented to mitigate heavy metal risks. For example, adding chemical agents, such as lime or

phosphates, can immobilize heavy metals in biosolids, reducing their bioavailability [75]. Using chelating agents that bind to heavy metals can prevent their uptake by plants and leaching into the soil [76]. At the same time, adjusting pyrolysis temperatures and residence times can affect the distribution and stability of heavy metals in biochar. Higher pyrolysis temperatures may convert metals into less bioavailable forms [19]. Adding materials such as clay or bioavailable iron during pyrolysis can immobilize heavy metals in the resulting biochar, making them less likely to leach into the soil [77]. Moreover, washing biochar with water or acid solutions can remove surface-bound heavy metals, reducing their potential for environmental contamination [78]. Post-pyrolysis thermal treatments can further stabilize heavy metals, reducing their mobility and bioavailability [78]. For soils contaminated by inappropriate biochar applications, growing plants known for their ability to accumulate heavy metals, known as hyperaccumulators, can help extract these contaminants from biochar-amended soils [79]. These plants can then be harvested and safely disposed of, reducing heavy metal concentrations in the soil [79].

In addition, to address the risks associated with heavy metals in BDB, strict regulations and guidelines have been established in various regions. For example, the European Commission has set stringent maximum levels (MLs) for heavy metals in biosolids used for agricultural purposes, including limits for Cd, Pb, Hg, and Cr. For example, its new MLs for Cd in various agricultural products are all set at the parts-per-billion (ppb) level, according to the European Commission Regulation 2023/915 [80]. Similarly, the United States Environmental Protection Agency (USEPA) regulates the use of biosolids through the 40 CFR Part 503 standards, which include limits for heavy metal concentrations [81]. These regulations ensure that only biosolids meeting specific safety criteria are applied to land, reducing the potential for heavy metal contamination.

4.3. Large-Scale Production

4.3.1. Issues and Barriers with Large-Scale Production

Scaling up the production of BDB involves addressing several technical, economic, and logistical challenges. First, variability in feedstock composition, pyrolysis conditions, and processing techniques can result in biochar with inconsistent properties [47]. This variability can affect the performance of BDB when applied to soils, making it difficult to predict its benefits reliably [19]. Second, optimizing the pyrolysis process to maximize yield and quality while minimizing costs is complex. Different temperatures, heating rates, and residence times can significantly affect the properties of the resulting biochar [19]. Third, the economic viability of BDB production depends on various factors, including capital investment, operational costs, market demand, potential revenue from biochar sales, and environmental benefits [82]. Fourth, creating a robust market for BDB requires awareness and acceptance among potential users, such as farmers, landscapers, and environmental remediation companies. Achieving economies of scale is essential for reducing the unit cost of BDB production [82]. However, this requires significant investment in infrastructure and technology.

4.3.2. Future Directions for Launching Large-Scale Production

Regarding the above challenges, the following efforts can be focused on in the near future: First, it is essential to develop standardized protocols for biochar production. These protocols should include guidelines for feedstock selection, pyrolysis temperature and duration, and post-production treatments. Certification programs, such as those by the International Biochar Initiative (IBI) or European Biochar Certificate (EBC), can help ensure compliance with these standards [18]. Second, extensive research and pilot studies are needed to identify the optimal conditions for BDB production. Advanced technologies, such as continuous-pyrolysis reactors, can enhance process efficiency and scalability. Collaboration between academia, industry, and government agencies can facilitate the development of best practices and technological innovations. Third, comprehensive economic feasibility studies are necessary to evaluate the costs and benefits of large-scale BDB

production. These studies should consider the entire value chain, from feedstock collection and transportation to pyrolysis and distribution. Incentives, such as carbon credits or subsidies for renewable energy projects, can improve the economic attractiveness of BDB production. Fourth, it is crucial to develop a marketing strategy that highlights the benefits of BDB, such as improved soil health, reduced greenhouse gas emissions, and enhanced crop yields. Demonstration projects and field trials can provide evidence of BDB's effectiveness, encouraging adoption. Finally, large-scale pyrolysis plants, strategically located near sources of biosolids and potential markets, can help achieve scale economies [82]. Cooperative models, where multiple municipalities or industries share pyrolysis facilities, can also be effective [83]. Public–private partnerships can provide the necessary funding and expertise to establish these facilities.

5. Conclusions

Biosolid-derived biochar (BDB) offers a valuable solution for converting waste into a resource beneficial for agriculture and environmental management. BDB enhances soil water and nutrient retention, boosts crop yields, and mitigates greenhouse gas (GHG) emissions, especially N_2O , CH_4 , and CO_2 . The pyrolysis process, whether slow, fast, or flash, is critical in determining biochar quality and effectiveness. However, scaling up BDB production requires overcoming challenges such as the need for standardized methods and economic feasibility studies. Solutions involve technological advancements, regulatory frameworks, and community education. Demonstration projects and public–private partnerships can provide necessary support, while cooperative models can achieve economies of scale and wider adoption. Future research should aim to optimize pyrolysis conditions, understand site-specific variability, and develop robust economic models. Addressing heavy metal content and potential toxic effects is essential for safe agricultural use. Overall, BDB is a sustainable, innovative solution for biosolid management and agricultural enhancement, contributing to a circular economy and environmental sustainability. Implementing BDB on a large scale can significantly reduce the environmental impact of biosolids and promote sustainable agricultural practices worldwide.

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