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Biochar - a Versatile Outcome of Various Biomasses - Benefits and Challenges

By Victor Lund[1,*], Rodrigo Salvador[1], M. Lynn Eriksen[1], Niels C. Kjærsgaard[1], Michael Hedegaard[1], Torben Knudby[1]

ABSTRACT:
Biochar, a porous carbon-rich material produced by pyrolyzing biomass under limited oxygen, is gaining attention for its ability to improve soil water retention and reduce nutrient leaching. This review analyses 18 peer-reviewed studies assessing the water absorption capacity of biochars derived from various agricultural residues. It examines how feedstock type, pyrolysis temperature, and soil characteristics influence biochar performance, focusing on water retention. Findings reveal that biochars effectiveness is closely tied to its physicochemical properties, which are shaped by both feedstock composition and pyrolysis conditions. Biochars produced at low (300–400°C) and high (≥600°C) temperatures enhanced water retention through different mechanisms: increased hydrophilicity at lower temperatures and greater surface area and porosity at higher ones. Sandy soil showed the greatest improvements, with some studies reporting up to a 628% increase in water holding capacity. These results suggest that biochar can reduce fertilizer use and nutrient runoff, promoting more sustainable agriculture and healthier aquatic ecosystems. The study highlights the need for standardized methods to assess water absorption capacity and calls for long-term field studies to validate laboratory findings under real-world conditions.

Key Words: Biochar, Water Retention Capacity, Pyrolysis Temperature, Feedstocks, Soil Moisture Dynamics, Nutrient Leaching

1. Introduction

Fish are dying in the Dansh lakes, streams, fjords and seas due to fertilizers washed into the water. A new report from Aarhus University shows that far more fertilizer continues to flow from the fields into the fjords and inland waters than they can tolerate (Politiken Nov. 2024). Why are the fish dying? When there is too little oxygen in the water, the fish cannot survive. Pollution with nutrients (e.g. nitrogen and phosphorus) from agriculture and wastewater promotes algae growth → algae die → bacteria break them down and use oxygen. So, if we can reduce nitrogen and phosphorus from flowing into the waters, then we save the fish. Some would say: Ban fertilizer, but that would reduce the yield from all the fields and Denmark would have to import most of its food. There are alternatives!

Salvatore, R. et al showed among other things, that biochar holds a wide range of properties related to carbon capture, soil improvement and water absorption. So, an

| [1]Technical University of Denmark (DTU), Department of Engineering Technology and Didactics, Lautrupvang 15, Ballerup Campus, DK-2750 Ballerup, Denmark;
*Corresponding author

alternative could be to analyze how water absorption can help to reduce water from leaching into the water streams, fjords and oceans.

Our hypothesis is that we should block nitrogen and phosphorus from getting into the water/ocean by using biochar. Biochar is known for its ability to absorb water – so if we add biochar to fields, the biochar will absorb the water (including nitrogen and phosphorus?), and the result would be that the farmers wouldn't have to use so much fertilizer (= saving money) because fertilizers would slowly be released when the fields become dryer.

2. Methods

We analyzed 18 papers from an initial pool of 100, using 6 screening criteria. Each paper was reviewed for 5 key aspects that mattered most to the research question.

Using our research question "What is the water absorption capacity of different types of biochars derived from agricultural waste materials?" AND ""What is the water absorption ability of different types of biochars". We screened papers that met these criteria:

1. **Agricultural Waste Source**: Is the biochar in this study derived from agricultural waste materials? (only in the first search for papers).
2. **Water Absorption Data**: Does the study report quantitative measurements of water absorption ability?
3. **Production and Characterization**: Does the study provide both a clear description of the biochar production process AND characterization of its physical/chemical properties?
4. **Methodology Quality**: Is this a laboratory-based experimental study with a clearly described methodology for measuring water absorption ability?
5. **Source Material Specification**: Does the study explicitly specify which agricultural material(s) were used as feedstock?
6. **Experimental Evidence**: Does the study include actual experimental data (rather than only theoretical models or predictions)?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper. We gave the model the extraction instructions shown below for each column.

- Type of study
- Feedstock Type
- Pyrolysis Temperature
- Soil types

Table 1: Characteristics of included Studies

Study	Study Design	Feedstock Type	Pyrolysis Temperature	Soil Types
Adhikari et al., 2023	Characterization	No mention found (locally sourced, commercial, standard biochars)	Not mentioned	Not mentioned
Bao et al., 2021	Laboratory, controlled relative humidity chamber	Water hyacinth, wood, chicken manure	300°C and 600°C	Not mentioned
Brantley et al., 2015	Laboratory	Poultry litter, pine woodchip	500°C (woodchip), 500–520°C (poultry litter)	Loam soil
Batista et al., 2018	Characterization	Green coconut shells, orange peel, oil palm bunch, sugarcane bagasse, water hyacinth, charcoal fines	350°C (oxygen-deficient)	Not mentioned
Downie et al. (2009)	Experimental	Wood-based (from pine, surface litter)	≥ 500°C	Sandy and clay soils
Huang et al., 2021	Experimental	Water hyacinth, chicken manure, wood	300°C, 600°C	Not mentioned
Jindo et al., 2014	Characterization	Rice husk, rice straw, apple tree wood chips, oak tree wood chips	400°C, 500°C, 600°C, 700°C, 800°C	Not applicable
Kameyama et al., 2019	Laboratory, biochar characterization	Cedar, cypress, moso bamboo, rice husk, sugarcane bagasse, poultry manure, wastewater sludge	400°C, 600°C, 800°C	Sandy agricultural soils
Khater et al., 2024	Characterization	Straw rice, sawdust, sugar cane, tree leaves	400°C, 600°C, 800°C	Not mentioned
Marshall et al., 2019	Laboratory	Grapevine cane and stalks	400–700°C	Vineyard soils
Ndede et al., 2022	Experimental	Woodchip, waterweed of Ludwigia grandiflora, poultry litter, bagasse	Not mentioned	Sandy agricultural soils
Novak et al., 2012	Experimental	Pecan shells, switchgrass (others not specified)	≥500°C, 700°C	Norfolk loamy sand, Declo silt loam, Warden silt loam
Piash et al., 2017	Characterization	Farmyard manure, water hyacinth, domestic organic waste, quick compost, corn cob, rice straw	Not mentioned	Not applicable
Rehman et al., 2020	Experimental	Dried cow manure	Not mentioned	Sandy loamy soils
Santos, 2022	Characterization	Sugar cane bagasse, dry coconut husks, green coconut husks, sludge, corn cobs, orange bagasse	550°C	Not applicable
Speratti et al., 2017	Experimental	Cotton husks, swine manure, eucalyptus sawmill residue, sugarcane filter cake	400°C, 500°C, 600°C	Brazilian Cerrado Arenosols

Suliman et al., 2017	Laboratory, microcosms, sand	Pine wood, hybrid poplar wood, pine bark	350°C and 600°C	Quincy sand
Wang et al., 2014	Experimental	Walnut shell, soft wood	600-700°C, 900°C	Silt clay loam, sandy loam

The reviewed studies utilized a wide variety of biochar feedstocks. Plant-derived biochars were the most common, featured in all ten studies. Manure-based biochars appeared in six studies, while wood-based biochars were used in five. Compost- and sludge-derived biochars were less frequent, each reported in one or two studies. Across the 18 studies reviewed, wood or wood-derived materials were the most frequently used, appearing in seven studies. Crop residues and manure were each used in five studies. Aquatic plant-based feedstocks were reported in three studies, and other materials—such as shells and husks—were also used in three.

Pyrolysis temperatures varied considerably among the studies. Temperature data were available for seven out of ten studies, with reported pyrolysis temperatures ranging from 300°C to 900°C. Notably, eight studies employed multiple temperature conditions. Pyrolysis temperature data were available for 15 of the 18 studies. Three studies used low-temperature pyrolysis (300–400°C), six studies reported intermediate temperatures (500–600°C), and six employed high-temperature pyrolysis (700–900°C).

Soil types examined across the studies were similarly heterogeneous. Information on soil type was reported in five studies. Sandy and loamy soil were the most frequently mentioned, each appearing in two to three studies. Additional soil types included silt loam, Arenosols, and silt clay loam. In three studies, soil type was considered "not applicable," but two studies did not mention soil type in their abstracts.

The second part of the analysis was to evaluate the actual water absorption effects. Here we also look at the surface properties.

Table 2: Effects of Biomass and Pyrolysis Temperature on Water Absorption

Study	Pyrolysis Temperature	Feedstock Type	Water Retention	Biochar surface properties
Bao et al., 2021	300°C, 600°C	Water hyacinth, wood, chicken manure	Water hyacinth biochar at 300°C: 82.41% hygroscopicity; at 600°C: 44.33%; chicken manure biochar and wood biochar unchanged; maximum moisture content 5–80%	Water hyacinth biochar pore volume and diameter increased with temperature; chicken manure biochar pore diameter decreased
Brantley et al., 2015	500°C, 500–520°C	Poultry litter, woodchip	Poultry litter biochar greater than woodchips in water retention ($P<0.05$); model coefficient a: 277.1 (poultry), 392.8 (woodchip); model coefficient b: -2.36 (poultry), -2.62 (woodchip)	Not mentioned

Huang et al., 2021	300°C, 600°C	Wood chips, Water hyacinth, Chicken manure	Higher at 300°C for water hyacinth	Not mentioned
Jindo et al., 2014	400-800°C	Rice husk, Rice straw, Wood chips	Not directly measured	Increased surface area and adsorption at higher temperatures
Kameyama et al, 2019	400°C, 600°C, 800°C	Various (wood, crop residues, manure)	Better at 600°C and 800°C for woodchips and sugarcane bagasse	Not mentioned
Khater et al., 2024	400°C, 600°C, 800°C	Straw rice, sawdust, sugar cane, tree leaves	Straw rice: 12.9–22.5 g/g; sawdust: 20.3–24.1 g/g; sugar cane: 24.9–27.6 g/g; tree leaves: 20.8–24.8 g/g; highest water holding capacity at 800°C	Porosity 45.9–63.7%; bulk density increased with temperature
Marshall et al., 2019	400–700°C	Grape cane	Grape cane biochar at 700°C: available water capacity 23% higher than clay soil; higher temperatures improved retention	Hydrophobicity at 400°C, not at higher temperatures; zeta potential, carbon, and ionic content linked to retention
Ndede et al, 2022	Not mentioned	Woodchip, waterweed, poultry litter, bagasse	Not mentioned	Not mentioned
Novak et al., 2012	≥500°C, 700°C	Pecan shells, switchgrass	Better for switchgrass biochar	Increased surface area, ash, C, and Si contents at higher temperatures
Piash et al., 2017	Not mentioned	Various (manure, crop residues)	Highest for water hyacinth (495%)	Not mentioned
Rehman et al., 2020	Not mentioned	Cow manure	1.5% increase per 1% biochar addition	Not mentioned
Santos, 2022	550°C	Various (crop residues, animal waste)	Varied from 88% to 628%	Not mentioned
Speratti et al., 2017	400°C, 500°C, 600°C	Cotton husks, swine manure, eucalyptus, sugarcane filter cake	Better for filter cake and eucalyptus	Not mentioned
Suliman et al., 2017	350°C, 600°C	Pine wood, hybrid poplar wood, pine bark	Switchgrass biochars significantly improved pot-holding capacity; effect varied by feedstock and temperature; no specific values	Higher temperature increased surface area, ash, carbon, and silicon content
Wang et al., 2014	600-700°C, 900°C	Walnut shell, soft wood	Improved for high surface area biochar	Higher surface area at higher temperatures

3. Water retention

Water retention effects were discussed in 15 studies. Five studies reported improved water retention at higher pyrolysis temperatures (≥600°C), while four reported enhanced retention at lower temperatures (around 300°C). One study found greater water retention associated with switchgrass-derived biochar, and another reported the highest water retention (495%) with water hyacinth biochar. Additionally, one study observed a 1.5% increase in water retention for every 1% increase in biochar application rate. Three studies reported wide variations in water retention, ranging from 88% to 628%. Santos et al (2022) showed up 628% water retention. While biochars capacity for water absorption has been widely investigated, a notable limitation in current research is the insufficient attention given to its ability to retain nutrients. This dual functionality—water retention and nutrient holding—is critical for evaluating biochar's overall effectiveness in soil amendment applications. Future studies should incorporate nutrient retention metrics to provide a more comprehensive assessment of biochar performance.

4. Application Rate Effects

Rehman et al. (2020) reported a 1.5% increase in water holding capacity for each 1% of biochar added to sandy loamy soils. Ndede et al. (2022) found that a 5% (volume/volume) biochar amendment could significantly improve the readily available water in sandy agricultural soils.

However, the relationship between application rate and water retention was not always linear. Ndede et al. (2022) noted that while water retention capacity increased with application rate, the readily available water peaked at 5-10% (volume/volume) biochar content for most biochar types. This suggests that there may be an optimal range for biochar application, beyond which additional benefits to water retention may diminish or even become negative.

5. Choices of Feedstock and the effect on Biochar absorption

The physicochemical properties of biochar, particularly its water retention capacity, are strongly influenced by the type of biomass feedstock used. Despite this, many studies lack a rigorous justification for their feedstock selection, limiting the reproducibility and comparability of results. There is a clear need for systematic investigations to identify which biomass sources yield the most sustainable and effective water retention outcomes across diverse soil types. This prompts a critical question for future research: is it feasible to develop a standardized, composite feedstock formulation capable of delivering consistent biochar performance across varying environmental conditions?

6. Soil Type Interactions

The effectiveness of biochar in enhancing soil water retention was found to vary across soil types, with sandy soils showing the most pronounced improvements. For instance, Wang et al. (2014) reported that biochar with high surface area significantly increased the water holding capacity of sandy soils (up to app. 42% increase - from 0,07 grams of water up to 0,1 grams of water per gram of dry soil). Similarly, Ndede et al. (2022) specifically targeted water retention enhancement in sandy agricultural soils.

Novak et al. ("Biochar Impact on Soil-Moisture Storage") evaluated the effects of biochar on three soil types—Norfolk loamy sand, Declo silt loam, and Warden silt loam—and found that switchgrass-derived biochar substantially improved water holding capacity across all soil textures tested.

Several studies further investigated the physical and chemical properties of biochar that may underline these effects. Four studies reported data on surface area and pore size or volume; three discussed hydrophobic or hydrophilic characteristics; and another three examined chemical or functional surface properties, such as zeta potential and surface functionality. One study included porosity and bulk density measurements. However, information on surface area and pore characteristics was lacking in three studies.

Collectively, these findings suggest that while sandy soils may derive the greatest benefit from biochar amendments, improvements in water retention can also occur across a range of soil textures when right biochar properties are matched to soil conditions.

7. Performance Factors

The physical characteristics of biochar, particularly surface area and porosity emerged as key determinants of its water retention capacity. Jindo et al. (2014) found that biochars produced at higher pyrolysis temperatures (≥500°C) exhibited greater surface area and enhanced adsorption potential. This was supported by Wang et al. (2014), who demonstrated that high surface area biochars improved water retention in sandy soils.

Particle size distribution also appears to be a relevant factor. Piash et al. (2017) reported that water hyacinth-derived biochar—exhibiting the highest recorded water holding capacity (495%)—also had the smallest average particle size (0.54 μm^2). These findings suggest that smaller particle sizes may enhance water retention by increasing surface area and total pore volume.

The studies show that lower pyrolysis temperatures (300–500°C) typically produce biochars with higher water retention due to the preservation of hydrophilic functional groups (Yuan et al., 2011). Conversely, higher temperatures (>600°C) tend to increase porosity but reduce hydrophilicity (Downie et al., 2009).

8. Environmental Conditions

Environmental conditions during water retention measurements varied widely among studies and were not consistently reported, complicating cross-study comparisons. Huang et al. (2021), for example, conducted their experiments in a controlled environmental chamber set at a constant temperature of 30°C and relative humidity ranging from 50% to 90%. Although this approach enables precise control over experimental variables, it may not accurately reflect field conditions.

Soil compaction state was another source of variability. Huang et al. (2021) explicitly examined water retention under both loose and dense soil conditions, while most other studies did not specify soil compaction levels.

On top of the looking like a viable way to reduce the leaching of nitrogen and phosphorus into the water streams, biochar also can enhance the quality of the soil (especially in areas with poor soil quality), as well as its carbon capture abilities.

This variability underscores the need for standardized methodologies in future biochar research to enable more meaningful comparisons and to better assess the influence of environmental and soil-specific factors on water retention outcomes.

9. Recommendations for Future Research

To advance understanding of biochars role in soil water retention, several key research priorities should be addressed:

9.1 Standardization of Water Absorption Capacity (WAC) Measurement Techniques

Currently, inconsistencies in WAC measurement methodologies hinder direct comparison across studies. Developing standardized protocols for assessing WAC under controlled and field-relevant conditions is essential for ensuring data comparability and reproducibility. Variability in pyrolysis parameters, environmental conditions—particularly soil type—and biomass feedstock selection continues to hinder the development of conclusive, evidence-based guidelines for agricultural practitioners and environmental policymakers. The lack of methodological consistency across studies limits comparability and generalizability of findings. Greater harmonization of experimental protocols and reporting standards is essential to enhance the validity and applicability of biochar research outcomes.

9.2 Nutrient Retention as a Limiting Factor in Biochar Studies

While biochar's capacity for water absorption has been widely investigated, a notable limitation in current research is the insufficient attention given to its ability to retain nutrients. This dual functionality—water retention and nutrient holding—is critical for evaluating biochar's overall effectiveness in soil amendment applications. Future studies should incorporate nutrient retention metrics to provide a more comprehensive assessment of biochar performance.

9.3 Long-Term Field Studies in Natural Soil Systems

Most existing research has been conducted under laboratory conditions or short-term experiments. Long-term field studies are needed to evaluate the sustained effects of biochar on water retention within real-world soil systems, accounting for environmental variability, plant–soil interactions, and biochar aging. Field studies would also be able to evaluate the extent to which these nutrients are retained during hydric uptake and to determine their temporal bioavailability to plants.

9.4 Investigation of Synergistic Effects in Blended Biochars and Targeted Optimization Strategies

The potential synergistic effects of blended biochars derived from mixed biomass feedstocks remain insufficiently explored. Future research should systematically investigate how combinations of different biochar types influence key soil properties—physical, chemical, and hydrological—with the aim of optimizing feedstock mixtures for specific agronomic or environmental applications. In particular, tailoring biochar formulations to address site-specific challenges, such as improving soil performance in drought-prone regions, represents a promising research direction. Detailed characterization of biochar properties, including particle size distribution, surface charge, and hydrophilic functional groups, could facilitate the development of engineered biochars with enhanced and predictable functionality for targeted soil amendment strategies.

9.5 Further Literature Review

The literature presents conflicting evidence regarding the influence of pyrolysis temperature on biochar's water retention capacity. For instance, Khater et al. (2024) report enhanced retention at higher pyrolysis temperatures, whereas Yuan et al. (2011) observe superior retention at lower temperatures. These discrepancies highlight the need for a more nuanced understanding of the interplay between pyrolysis conditions and biochar functionality. Future research should aim to reconcile these divergent findings by identifying the specific environmental, feedstock, and methodological factors under which opposing effects emerge, thereby contributing to a more unified framework for biochar optimization.

10. Conclusion

This review underscores biochars significant potential as a multifunctional soil amendment, particularly in enhancing water retention and mitigating nutrient leaching. The findings from 18 peer-reviewed studies reveal that biochars effectiveness is highly contingent upon feedstock type, pyrolysis temperature, and soil characteristics. Agricultural residues such as water hyacinth, sugarcane bagasse, and straw rice consistently showed high water absorption capacities, with retention rates reaching up to 628% in some cases.

Lower pyrolysis temperatures tend to preserve hydrophilic functional groups, enhancing water retention, while higher temperatures increase porosity and surface area, contributing to improved adsorption. Sandy soils appeared as the most responsive to biochar amendments, though benefits were seen across various soil textures. Importantly, the relationship between biochar application rate and water retention is not strictly linear, suggesting the need for optimized dosing strategies.

Despite promising laboratory results, the variability in experimental conditions and lack of standardized methodologies present challenges for broader application. Long-term field studies and standardized water absorption measurement protocols are essential to confirm biochars performance under real-world conditions. Furthermore, exploring synergistic effects of blended biochar types could unlock new pathways for tailored soil management solutions.

In conclusion, biochar stands for a promising tool for sustainable agriculture and environmental protection. Its ability to keep water and nutrients offers a viable strategy to reduce fertilizer runoff, protect aquatic ecosystems, and enhance soil health. However, realizing its full potential requires coordinated research efforts, policy support, and practical implementation frameworks.

The proposition that biochar can simultaneously mitigate fertilizer runoff and enhance soil health carries significant policy relevance. Translating these scientific insights into actionable strategies will require the development of cost-effective, scalable implementation frameworks suitable for both smallholder and large-scale agricultural systems. Bridging the gap between research and practice will be essential to support widespread adoption and to realize biochar's potential as a tool for sustainable land management.

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