

## Hydrochar – A Sustainable Solution for Soil Health and Waste Management

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### SUMMARY

Hydrochar is a carbon-rich material produced through hydrothermal carbonization (HTC) of wet organic waste like agricultural residues and sewage sludge. Unlike biochar, it is suitable for high-moisture feedstocks and offers multiple benefits for sustainable agriculture and waste management. It enhances soil physical, chemical and biological properties, improves nutrient retention and water holding capacity and aids in carbon sequestration and soil remediation. Hydrochar also supports microbial activity, increases crop productivity and promotes circular economy principles. However, challenges remain in optimizing production and understanding long-term impacts, requiring further research for widespread adoption.

### INTRODUCTION

Hydrochar is emerging as a revolutionary material in the quest for sustainable agricultural practices and efficient waste management. Produced through the process of hydrothermal carbonization (HTC), hydrochar is generated by treating organic biomass—including agricultural residues, food waste, and sewage sludge—under relatively low temperatures (180–250°C) and saturated pressure in the presence of water. This process mimics natural coal formation but occurs over hours rather than millennia, making it both rapid and resource-efficient. The resulting product is a carbon-rich, porous material with multiple agronomic and environmental benefits. Unlike traditional composting or pyrolysis-based biochar, HTC does not require dry feedstocks, making it particularly suitable for wet waste, which constitutes a major portion of municipal and agro-industrial waste streams. This gives hydrochar a significant edge in waste valorization, transforming what would otherwise be pollutants into a value-added soil amendment. From a soil health perspective, hydrochar contributes to improved soil structure, water retention, cation exchange capacity (CEC), and nutrient availability. It can act as a slow-release fertilizer, reducing nutrient leaching and improving plant nutrient uptake. Furthermore, its high carbon content contributes to long-term carbon sequestration, aiding in the mitigation of climate change by locking atmospheric carbon into soil systems. In addition to enhancing soil fertility, hydrochar has the potential to immobilize toxic metals and organic contaminants, thereby assisting in soil remediation efforts. Its positive impact on microbial communities and soil enzymatic activities also supports the biological health of soils, fostering sustainable crop production systems. Given its dual role in sustainable agriculture and integrated waste management, hydrochar stands as a viable tool in advancing circular economy principles.

### What is Hydrochar?

Hydrochar is a carbonaceous product derived from organic feedstocks such as agricultural residues, food waste, and sewage sludge (Sharma *et al.*, 2024). Unlike biochar, which is produced via pyrolysis, hydrochar is generated in a water-rich environment, making it a more suitable option for wet feedstocks. The HTC process mimics natural coal formation but compresses it into a few hours, creating a highly stable and nutrient-rich material.



**Hydrochar**

## Key Benefits of Hydrochar

Hydrochar offers a multifaceted array of benefits, making it a valuable tool for advancing sustainable development goals. As a carbon-rich product derived from the hydrothermal carbonization (HTC) of wet organic wastes, hydrochar serves as an effective soil conditioner with the potential to transform conventional agricultural and waste management practices. It significantly enhances soil water retention capacity, improves soil structure, and increases porosity and aeration, which are critical for root development and crop productivity. Moreover, hydrochar acts as a slow-release source of essential plant nutrients—including nitrogen (N), phosphorus (P) and potassium (K)—thereby reducing nutrient leaching losses and enhancing nutrient use efficiency (Masoumi *et al.*, 2021). Beyond improving soil fertility, hydrochar plays an instrumental role in long-term carbon sequestration. Its stable carbon form resists microbial decomposition, enabling carbon to remain in the soil for extended periods. This characteristic helps in mitigating greenhouse gas emissions, making hydrochar a viable tool in climate change adaptation and mitigation strategies. Additionally, it improves soil buffering capacity and helps in detoxifying contaminated soils by immobilizing heavy metals and organic pollutants, thereby aiding in soil remediation. The hydrothermal carbonization process itself presents a sustainable waste management solution. Unlike conventional thermal processes that require dry biomass, HTC can process high-moisture feedstocks such as food waste, sewage sludge, and crop residues without prior drying. This not only reduces energy consumption but also diverts organic waste from landfills, cutting down methane emissions and leachate generation. The HTC process also produces process water enriched with nutrients and dissolved organics, which can be further treated or recycled. Integrating hydrochar into agricultural systems helps reduce dependence on synthetic chemical fertilizers, thereby lowering production costs and minimizing the environmental footprint of farming. It supports the development of eco-friendly, regenerative farming systems, especially under conditions of degraded or nutrient-deficient soils. Additionally, the use of hydrochar aligns with the principles of circular bioeconomy and zero-waste agriculture, by converting waste into a valuable input that supports crop productivity, environmental health, and economic resilience.

## Applications of Hydrochar

Hydrochar finds diverse applications across various sectors, showcasing its versatility and environmental benefits. In agriculture, it enhances soil fertility and boosts crop productivity by improving nutrient availability and soil structure. Its remarkable ability to adsorb heavy metals and contaminants makes it a valuable tool for environmental remediation, aiding in the cleanup of polluted soils and water bodies. Hydrochar also holds potential in the energy sector, serving as a precursor for biofuels or as an alternative energy source. Additionally, it plays a critical role in waste treatment by providing a circular economy solution, converting organic waste into a sustainable and valuable resource (Usman *et al.*, 2019).

## Role of Hydrochar in Soil Health

Hydrochar plays a vital role in improving and maintaining soil health by influencing its physical, chemical, and biological properties. Its unique characteristics—such as porous structure, high surface area, and nutrient-rich composition—make it a promising amendment for enhancing soil quality, particularly in degraded or nutrient-deficient soils. Below is a detailed breakdown of how hydrochar contributes to different aspects of soil health:

### 1. Improvement in Soil Physical Properties

Hydrochar application enhances several physical attributes of soil that are crucial for root growth and water dynamics:

**Soil Structure and Porosity:** The porous and fibrous structure of hydrochar improves soil aggregation and aeration. This facilitates better root penetration and gas exchange in the root zone.

**Bulk Density Reduction:** Hydrochar has a low bulk density, which reduces the overall density of heavy or compacted soils, thereby improving root development and tillage ease.

**Water Holding Capacity (WHC):** Hydrochar increases the soil's ability to retain water, especially in sandy and drought-prone soils. This enhances water availability during critical growth periods and reduces irrigation requirements.

**Erosion Control:** By stabilizing aggregates and improving surface cover, hydrochar helps reduce erosion by wind and water, thereby preserving topsoil and associated nutrients.

## 2. Enhancement of Soil Chemical Properties

Hydrochar alters the chemical environment of the soil, supporting both nutrient availability and buffering capacity:

**Nutrient Retention and Availability:** Hydrochar contains macro- and micronutrients such as N, P, K, Ca, and Mg. It functions as a slow-release fertilizer, reducing nutrient losses via leaching or volatilization (Masoumi *et al.*, 2021).

**Cation Exchange Capacity (CEC):** The functional groups on hydrochar (e.g., carboxyl, hydroxyl) enhance the soil's CEC, improving its ability to retain and exchange nutrient cations like  $\text{NH}_4^+$ ,  $\text{K}^+$ , and  $\text{Ca}^{2+}$ .

**pH Moderation:** Depending on feedstock and process conditions, hydrochar can help neutralize acidic soils or buffer pH extremes, promoting optimal nutrient uptake.

**Immobilization of Contaminants:** Hydrochar can adsorb heavy metals (e.g., Pb, Cd, Zn) and organic pollutants, reducing their bioavailability and toxicity to plants and microbes. This makes it especially useful in remediation of contaminated soils.

## 3. Stimulation of Soil Biological Activity

Biological health is a key indicator of sustainable soil function and hydrochar contributes positively in this regard:

**Microbial Biomass and Diversity:** Hydrochar provides habitat and energy sources for beneficial soil microorganisms, leading to increased microbial biomass and enzymatic activity.

**Soil Enzyme Activities:** Enzymes such as dehydrogenase, urease, and phosphatase, which are indicators of microbial function and nutrient cycling, have been shown to increase with hydrochar application.

**Promotion of Symbiotic Organisms:** Hydrochar has been found to enhance the activity of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, which facilitate nutrient uptake and plant resilience.

## 4. Soil Organic Carbon (SOC) Enrichment and Carbon Sequestration

**Stable Carbon Pool:** Hydrochar is rich in stable organic carbon that resists decomposition, contributing to long-term carbon storage in soils.

**Carbon Sequestration Potential:** Incorporation of hydrochar helps in offsetting atmospheric  $\text{CO}_2$  emissions, making it an important tool in climate-smart soil management.

**Microbial Carbon Use Efficiency:** The presence of hydrochar improves microbial processing of organic matter, increasing the efficiency of soil carbon cycling.

## 5. Support for Plant Growth and Yield

Indirectly, by improving soil physical, chemical, and biological properties, hydrochar:

- Enhances seed germination and root proliferation.
- Improves nutrient and water uptake.
- Reduces plant stress under drought or salinity conditions.
- Ultimately increases crop yields and biomass production.

## Challenges and Research Needs

Despite its promising potential, the widespread adoption of hydrochar faces several challenges. These include understanding its long-term environmental impacts, optimizing HTC process parameters for diverse feedstocks, and improving economic feasibility. Researchers are also exploring ways to tailor hydrochar properties for specific applications through chemical and physical modifications.

## CONCLUSION

Hydrochar stands out as a versatile and sustainable material with immense potential to address critical global challenges. Its ability to improve soil health, sequester carbon, manage organic waste, and support sustainable agriculture makes it a key component in advancing environmental sustainability. With its wide range of applications, including agriculture, environmental remediation, energy production, and waste treatment, hydrochar offers a practical solution to promote circular economy principles and mitigate climate change. However, further research is needed to optimize production processes, evaluate long-term impacts, and enhance

economic feasibility. By integrating hydrochar into mainstream practices, we can pave the way for a greener and more resilient future.

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