

## AN OVERVIEW OF HYDROTHERMAL CARBONIZATION FOR HYDROCHAR PRODUCTION: PROCESS OPTIMIZATION AND APPLICATION POTENTIAL

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### ABSTRACT

*In today's world, high energy use brought on by advanced technology, industrial growth, population increase, and even geopolitical conflicts is putting heavy pressure on energy sources. This excessive consumption of energy raises concerns about depleting these sources. Additionally, burning fossil fuels releases a significant amount of CO<sub>2</sub> that threatens our environment. As a result, people all over the world are now turning toward renewable energy to reduce environmental impact. Hydrothermal Carbonization (HTC) process is an environment-friendly technology. It is a thermochemical conversion process that uses heat to convert wet waste and biomass feedstocks to hydrochar. This review article reflects the potential to achieve maximum hydrochar yield using different lignocellulosic biomass in the HTC process. It focuses on how temperature, among all parameters in HTC, significantly impacts yield. Critical temperatures for various cases are identified and correlated with the highest possible hydrochar yield produced during the HTC process. This analysis provides insight into optimizing temperature conditions for more effective hydrochar production. This study also explores the practical use of hydrochar as an energy source and as a soil amendment, which can improve soil fertility in agriculture. With its high carbon content, hydrochar has many other applications, such as reducing leaching, supporting bioenergy production, serving as a catalyst, and aiding in carbon sequestration. The review also discusses the potential areas for expanded application of hydrochar for a sustainable environment.*

**Keywords:** Hydrochar, Hydrothermal carbonization, Lignocellulosic biomass, Bioenergy

### INTRODUCTION

The generation of waste has grown to be a major worldwide concern due to industrial activity, population increase, and urbanization. This increasing amount of garbage creates major problems, such as resource depletion, contamination of the environment, hazards to public health, and greenhouse gas emissions causing climate change. As a result, effective waste management is vital for limiting environmental contamination, public health risks, and greenhouse gas emissions. Traditional waste biomass management methods, such as composting or dumping in open landfills, pollute the environment, incur economic losses, and pose health risks. Biomass is a vital renewable resource and energy source, even though it is seen as waste (Cavali et al., 2023; Masoumi et al., 2021a; T. Wang et al., 2018). Embracing waste as an energy source provides a long-term solution for pollution reduction, renewable energy generation, and environmental protection. One of the most prevalent renewable energy sources is biomass, which is regarded as a sustainable energy source. When the moisture content of biomass is greater than 30 weight percent, it is categorized as wet; when it is less than 30 weight percent, it is defined as dry. This classification would determine the conversion technologies to be used. Wet biomasses include things like algae, sewage sludge, animal manure, and industrial effluents, while dry biomasses include things like woody, herbaceous, and agricultural biomass (Masoumi et al., 2020; Vassilev et al., 2010). The conversion of biomass to biofuels can be achieved through thermochemical and biological processes. To make biofuels, biomass goes through a series of complex chemical events, including dehydration, decarboxylation, decarbonylation, and depolymerization (Masoumi et al., 2021b). Two methods of thermochemical conversion technology for the synthesis of bio/hydrochar as the major output are pyrolysis HTC (Figure 1). These thermochemical methods are used to transform biomass containing organic molecules into carbon-rich products. The hydrothermal carbonization method is thought to be a promising technology because it eliminates the

drying step, as opposed to sluggish pyrolysis. Furthermore, HTC is widely considered economically viable for wet biomass.

Most of the time, HTC is done at temperatures between 180°C and 240°C for 5–240 minutes at subcritical water pressures (Mumme et al., 2011; Shen, 2020). The products are categorized as liquid phase, gas phase, and biochar, which is not completely carbonized (Leng & Huang, 2018; Papari & Hawboldt, 2018). The need for carbon-based materials has gradually grown in recent years. Furthermore, one of the environmental issues has been the high expense of producing carbon compounds like activated carbon using non-renewable petroleum precursors. As a result, the need to manufacture carbon materials from renewable resources has grown by 10% annually on a global scale (Ayinla et al., 2019; Namazi et al., 2016). Hydrochar has so drawn a lot of interest because its feedstocks are accessible, inexpensive, and renewable (Cheng & Li, 2018b; Hu et al., 2010). The manufacturing and use of hydrochar have recently attracted more attention. This review article illustrates how various lignocellulosic biomass can be used in the HTC process to maximize the yield of hydrochar. It focuses on how yield is greatly impacted by temperature, out of all the HTC parameters. The maximum hydrochar yield generated during the HTC process is associated with the critical

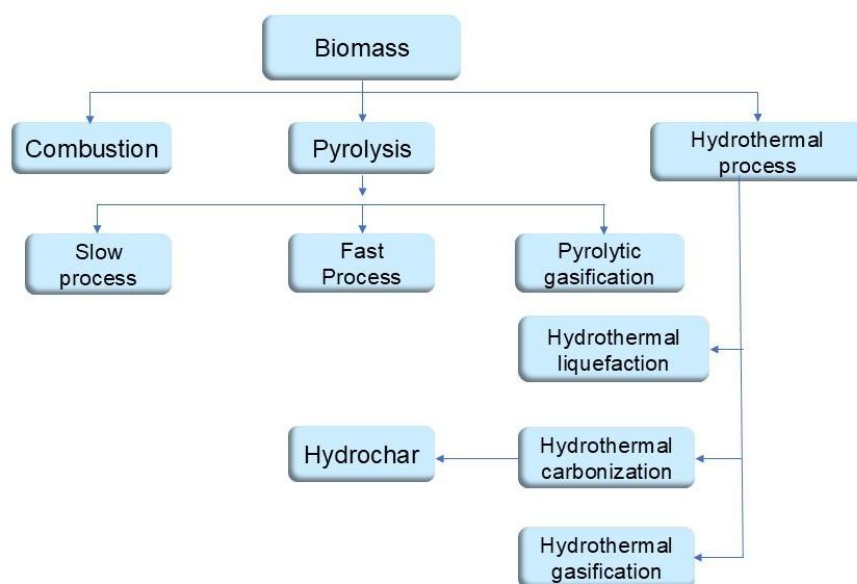


Figure 1 Conversion pathways from biomass to hydrochar.

temperatures for different scenarios. This investigation sheds light on how to best regulate temperature for the generation of hydrochar. The practical applications of hydrochar as a soil amendment and energy source that can increase soil fertility in agriculture are also examined in this work. Because of its high carbon content, hydrochar can be used for a variety of different purposes, including lowering leaching, promoting the generation of bioenergy, acting as a catalyst, and assisting in the sequestration of carbon.

## METHODOLOGY

HTC is a thermochemical process that converts wet biomass into carbon-rich solid products like hydrochar using hot and pressured water. The following is a structured explanation of the approach of the hydrothermal carbonization process.

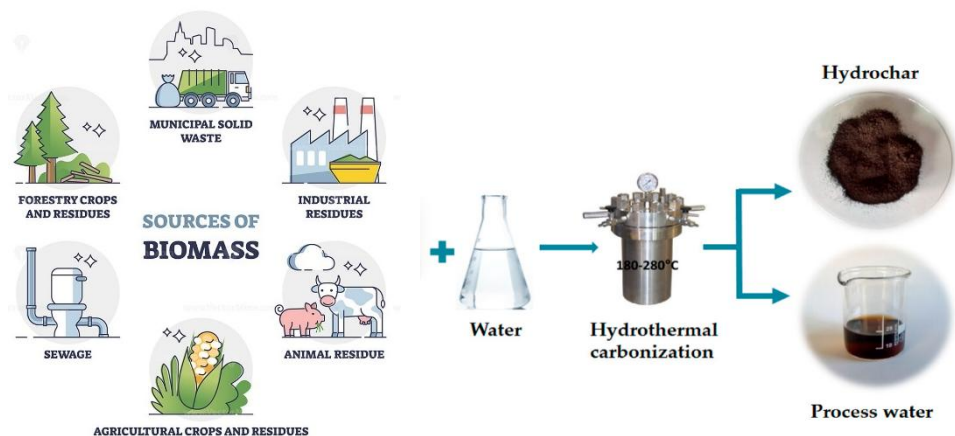


Figure 2 HTC Process Control (Petrović et al., 2024a).

Figure 2 represents the schematic diagram of the HTC process. The HTC process is an environmentally friendly technique. This process turns biomass feedstocks into high-carbon, smokeless solid fuels (Chembukulam et al., 1981; Kruse et al., 2013). The HTC of biomass with water has been studied at high temperatures (180-250 °C) and excessive pressure (2-10 MPa) for several hours (Xiao et al., 2012). The conversion of cellulosic material to high carbon material. The cellulose and water mixture was heated to 250-310 °C in a closed vessel (Jamari & Howse, 2012). Consequently, a solid with a reduced O/C ratio was generated, indicating that HTC was a successful conversion process vessel (Jamari & Howse, 2012). The HTC process can be either direct or catalytic. In the direct HTC method, only water and feed are heated in a reactor at varying temperatures without a catalyst, while the catalytic HTC process uses a catalyst. HTC produces solid, liquid, and gaseous products (Funke & Ziegler, 2010). Hydrothermal processes have a wide range of applications due to the significant shifts in water characteristics at various temperatures. HTC uses water as a solvent and reaction media, whether from the biomass or from the process itself (Libra et al., 2011). Since the previous decade, investigations have shown that HTC is a promising technique for converting biomass into various products (M. M. Titirici et al., 2007; M.-M. Titirici et al., 2007, 2008).

### INFLUENCE OF PROCESS PARAMETERS

Several major parameters regulate the physicochemical transformation of biomass into hydrochar, which influences the efficiency and outcome of the HTC process. The chemical and physical features of hydro chars produced from the same feedstock might vary significantly if certain operating parameters are modified. As a result, understanding the impact of each parameter is critical for optimizing the HTC process and producing the desired product (hydrochar)(Karagöz et al., 2005; Wilk et al., 2021). The next paragraphs provide a more in-depth explanation of the impact.

### EFFECTS OF FEEDSTOCKS

The feedstock used in biochar manufacturing has a considerable impact on the biochar's characteristics and quality. The carbon percentage of the finished biochar is directly impacted by the carbon contents of the various feedstocks. For instance, wood contains more carbon than animal manure or agricultural waste. Because of its stability and capacity to store carbon in the soil, biochar with a higher carbon content is frequently preferred. Nitrogen-rich feedstocks (such as manure) create biochar with a greater nitrogen content. This can improve soil fertility, but it may also result in the emission of volatile nitrogen molecules during pyrolysis. On the other hand, feedstocks such as leaves or straw have lower nitrogen levels, which may result in biochars with fewer nutrients but greater carbon sequestration capability. Hardwood and other feedstocks with a higher lignin concentration typically provide biochar with more surface area and porosity. This can increase the biochar's efficacy for uses like pollutant adsorption, water filtering, and soil amendment. There are many types of biomasses depending on the environment, development time, compositional material, etc. Among them, the significant biomasses are: cellulose, hemicelluloses, and lignin. Various forms of biomass introduce various amounts of hydrochar, and the usable hydrochar can be Mixwood, Microalgae, Olive Mill Wastewater, Empty Fruit Bunch, Eucalyptus Sawdust, Barley straw, Poplarwood, Olive wastes, Wheatstraw, Palmshell, and Switchgrass. Wood and woody biomass, herbaceous and agricultural biomass, aquatic biomass, animal and human biomass waste contaminated biomass, and industrial biomass waste (semi-biomass) biomass mixtures are those classification(Nizamuddin et al., 2017). The maximum yield significantly depends on the type of

biomass. The sawdust can also be used as the raw material of biomass where sieved sawdust was chemically characterized in terms of ash content, water content, volatile matter, fixed carbon content, lignocellulosic content, and heating value(Oktaviananda et al., 2017). Canteen waste consisting of a mix of rice, pasta, meat, vegetables fruits, etc. can be used as feedstock for optimum yield production (Zabaleta et al., 2017). Biomass has a higher content, which results in more char generation due to the complicated branching of higher content that remains as residue(Peterson et al., 2008).

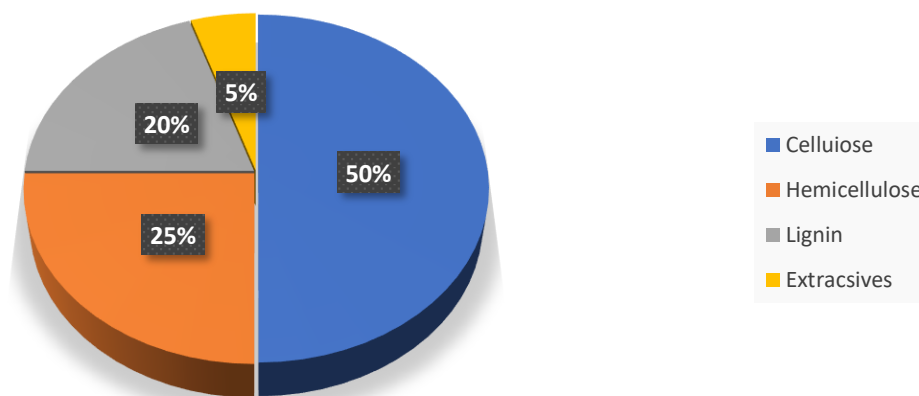


Figure 3 Typical composition of biomass(Nizamuddin et al., 2017)

Experiments show that increasing lignin content leads to less bio-oil and more biochar synthesis. Repolymerization and cyclization of lignin fragments in liquid oil lowered its output(Demirbaş, 2000). At 400°C, cellulose was reduced by 94.5%, hemicellulose by 80%, and lignin by 54.3%. Higher lignin content in biomass leads to greater char production during decomposition(Thomsen et al., 2008). This demonstrated that more char is made when material with more lignin is broken down(Gani & Naruse, 2007; Karagöz et al., 2005; Thomsen et al., 2008).

### EFFECTS OF TEMPERATURE AND RETENTION TIME

Temperature plays a vital role in the HTC process, altering reaction routes, product composition, and overall efficiency. Understanding the effects of temperature on HTC is critical for improving the process for certain applications and the production of maximum yield. Higher temperatures significantly affect the degradation process and the number of chemicals that can be hydrolyzed(Ro et al., 2020; Wilk et al., 2021; T. Wang et al., 2018b; Funke & Ziegler, 2010b). The lignocellulosic biomass begins to decompose more rapidly at temperatures above 180 °C(Jung et al., 2018). Although a higher carbonization temperature influences the creation of hydrochar with a higher carbon content, it also decreases the solid phase yield because of increased degradation . As the temperature rises, biomass conversion becomes more effective. This is typically caused by the temperature providing more energy to break the bonds in the biomass(Akhtar & Saidina Amin, 2012). Moderate temperatures often give more oil, whereas higher temperatures mostly produce gas and char. Hydrochar can be produced through secondary breakdown, Bourdard gas reactions (which favor gas generation), or recombination of free radical processes (which yields more char) (Gaskin et al., 2008) (Mazaheri et al., 2010). The study compared the effect of temperatures ranging from 150-375°C on two forms of biomass: coconut fiber and eucalyptus leaves. This indicated that increasing the temperature to 350°C significantly reduces solid production for both feed materials(Liu et al., 2013).

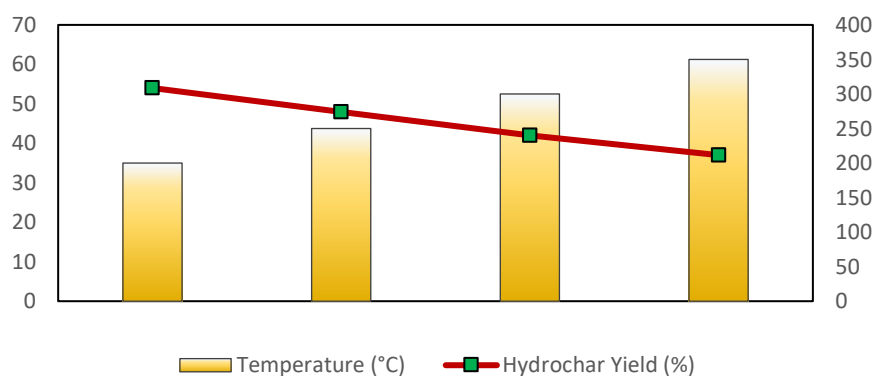


Figure 4 Hydrochar yields at treated temperature

The figure represents the hydrochar yields at 200°C, 240°C, 270°C, 300°C, and 330°C were determined to be 54.44%, 49.45%, 47.67%, 42.31%, and 38.82%, respectively, after the hydrothermal treatment operations. The maximum yield, 54.44%, was obtained at 200°C, while the lowest, 38.82%, was obtained at 330°C. As temperature rises, the energy density ratio may increase. Increasing the temperature of a reaction reduces yield but increases calorific value (Oktaviananda et al., 2017; Yao et al., 2016). The generation of biochar is also affected by the reaction process's retention period. The generation of biochar is also affected by the reaction process's retention period. A longer residence time intensifies the reaction, affecting solid recovery and resulting in more stable hydrochars with a polyaromatic structure. Secondary hydrochar production in lignocellulosic biomass is determined by residence time, whereas non-dissolved monomers are more affected by temperature (Azzaz et al., 2020; Khan et al., 2021).

Table 1 Review of hydrochar synthesis using HTC process for maximum yield

Biomass feed type	Temperature (°C)	Retention Time (min)	Solid yield (%)	Reference
Mixwood	215–295	5-60	50.1–69.1	(Hoekman et al., 2011a)
Microalgae	190–210	30-120	25.3–45.7	(Heilmann et al., 2010)
Olive mill wastewater	180-220	840	~30	(Poerschmann et al., 2013)
Empty fruit bunch	150–350	20	49–76	(Parshetti et al., 2013)
Eucalyptus sawdust	250	120	40	(Sevilla et al., 2011)
Barley straw			37	(Nizamuddin et al., 2017)
Poplar wood	180–230	480	51.9–89.9	(Wiedner et al., 2013)
Olive residues			49.0–75.4	(Nizamuddin et al., 2017)
Wheat straw			53.7–80.1	(Nizamuddin et al., 2017)
Palm shell	180–260	30–120	38.7–63.0	(Nizamuddin et al., 2016)
Switch grass	300–400	60–180	35.2–82.0	(Sadaka et al., 2014)
Wood chip	240	60	26.80 30.05	(G. Wang et al., 2023)

Spent mushroom substrate	180	60	57.2	(Kojić et al., 2021)
	200		55.23	
	240		43.79	
	260		41.98	
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Soybean residue	200	120	42.9	(Ahmad et al., 2021)
	250		37.4	
	300		32.3	
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Swine manure	200	0-60	58.7	(Xiong et al., 2019)
	220		56.3	
	240		55.7	
	260		51.7	
	280		50.2	
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Banana stalk	160	60	75.3	(Islam et al., 2019)
	160	120	73.6	
	160	180	72.8	
	180	60	68.2	
	180	120	65.2	
	180	180	61.5	
	200	60	61.8	
	200	120	60.9	
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Miscanthus	180	60	73	(Mihajlović et al., 2018)
	200		54	
	220		51	
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Tobacco stalk	180	120	80	(Cai et al., 2016)
	200		67	
	220		61	
	240		63	
	260		59	
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Grape pomace	180	60	86	(Petrović et al., 2016)
	200		78	
	220		66	

The table presents an overview of hydrochar synthesis using the HTC process for various biomass feedstocks, including temperature ranges, retention time, and solid yield percentages. Various biomass types were investigated, including mixed wood, microalgae, olive mill effluent, empty fruit bunches, eucalyptus sawdust, barley straw, poplar wood, olive leftovers, wheat straw, palm shells, and switchgrass. Solid output varies from ~30% for olive mill effluent to 89.9% for poplar wood at temperatures ranging from 150°C to 400°C, depending on feedstock. Several studies have shown that biomass type and operating parameters affect hydrochar output. Poplar wood has a maximum yield between 51.9% - 89.69% at temperatures ranging from 180 to 230 °C. The yield from lignocellulosic biochar varies with the process temperature. The table indicates that a greater temperature will reduce the yield. Temperatures between 180°C and 250°C are optimal for best yield. The generation of biochar is also affected by the reaction process's retention period. A longer residence time intensifies the reaction, affecting solid recovery and resulting in more stable hydrochars with a polyaromatic structure. Secondary hydrochar production in lignocellulosic biomass is determined by residence time, whereas non-dissolved monomers are more affected by temperature. The table also shows that the yield is dependent on the reaction's retention period. For maximum yield, different biomasses have varying retention durations. In conclusion, based on the hydrochar produced, the residence time needs to be taken into account in order to synthesize the hydrochar at a particular temperature.

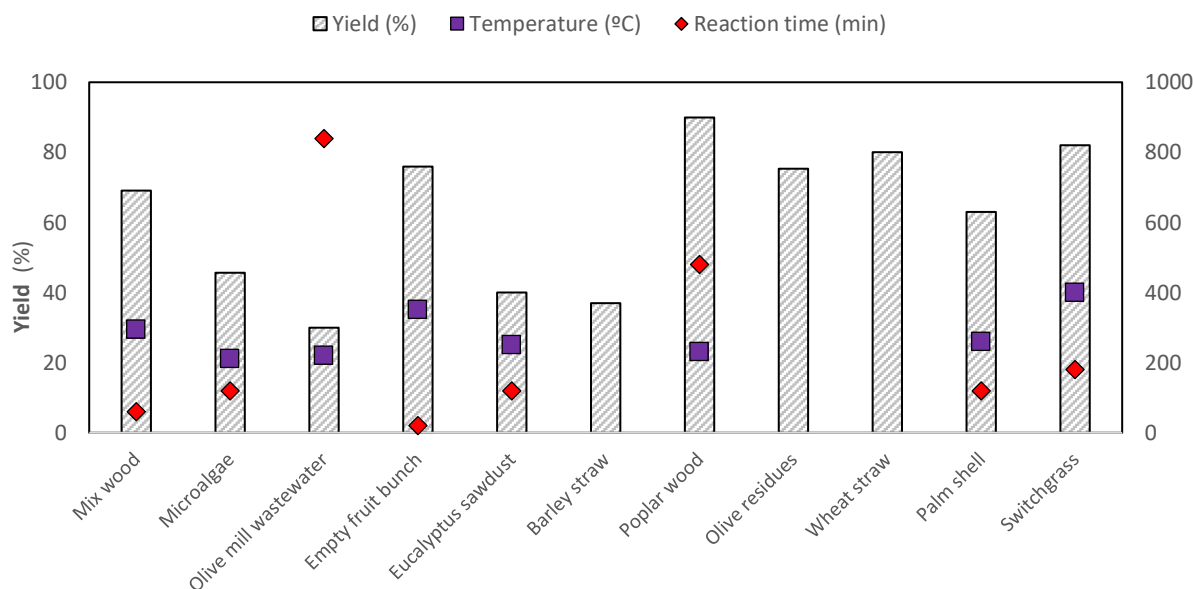


Figure 5 Hydrochar synthesis using HTC of different biomass.

The figure depicts the relationship between yield %, temperature, and reaction time in the HTC process. The left vertical axis represents the solid yield %, while the data points show differences in reaction time, which is given in minutes. The right vertical axis shows the temperature (°C). For a variety of feedstocks, HTC parameters like temperature and retention duration have a major impact on the final product's quality and solid output. As indicated by microalgae (25.3–45.7% yield at 190–210°C), raising the temperature generally accelerates the breakdown of biomass, lowering solid yields because solids are converted into liquid and gaseous products (Heilmann et al., 2010). Similar to this, extended retention periods encourage more thorough hydrolysis and carbonization, which frequently results in a further decrease in the solid production, as seen with effluent from olive mills (~30% yield after 840 minutes) (Poerschmann et al., 2013). Conversely, feedstocks with a high solid yield range (51.9–89.9%) and moderate operating temperatures (180–230°C) and long retention periods (480 minutes), such as poplar wood, show increased biomass retention and the potential to produce high-quality biochar (Wiedner et al., 2013). The figure's key trends indicate that at lower temperatures (e.g., below 200°C), yields are quite high (Xiong et al., 2019). However, as the temperature rises above 200°C, the yield typically declines. Reaction time also effects yield: shorter reaction times at moderate temperatures result in higher yields, whereas longer reaction times result in lower yields. This means that both temperature and reaction time must be carefully tuned to balance solid yield and energy efficiency for different biomass feedstocks.

### CHARACTERISTICS OF HYDROCHAR DERIVED FROM HTC

Proper examination of hydrochar is crucial for its effective use as a fuel source. The products conducted a proximate analysis to determine volatile matter (VM), ash, and fixed carbon (FC) content. HTC significantly altered the hydrochar elemental compositions, as indicated by the H/C and O/C ratios. This corroborated the degree of carbonization of the Hydrochar (T. Wang et al., 2018c). Hydrochar with high FC and low VM content can beat raw biomass as a solid fuel due to its ease of ignition at low temperatures (about 250°C) and quick weight loss (Tekin et al., 2014). Lignocellulosic biomass polymers, including lignin, have a high aromatic content. These natural properties favor the formation of hydrochar with high FC (T. Wang et al., 2018c). When assessing the level of de-oxygenation and the aromatic content during the HTC of biomass, the H/C and O/C ratios serve as vital parameters (Tekin et al., 2014). They offer ideas on the aromatic level; a greater H/C ratio denotes a lower hydrochar aromatic content (Tekin et al., 2014). Increasing the hydrothermal temperature or retention time resulted in lower H/C and O/C ratios for all hydrochar. The ratio shift can identify reaction pathways such as dehydration (H<sub>2</sub>O) and decarboxylation (CO<sub>2</sub>, carbonyls, and carboxylic acids) during HTC (Hoekman et al., 2011b). Lignocellulose-derived hydrochar exhibited higher coalification than sludge-derived hydrochar, highlighting the importance of natural composition during HTC (Tekin et al., 2014). After conducting mass balance analyses on the carbon distribution in HTC of MSW, it became apparent that the hydrochar had a significant amount of aromatic carbon, resulting in lower H/C and O/C ratios (Berge

et al., 2011). In conclusion, understanding the physiochemical properties of hydrochar is critical for its effective application.

## APPLICATIONS OF HYDROCHAR

Because of its distinct physical and chemical characteristics, hydrochar—a carbon-rich substance made by hydrothermal carbonization (HTC) of biomass—has a variety of uses. Figure 6 represents the potential application of the produced hydrochar.

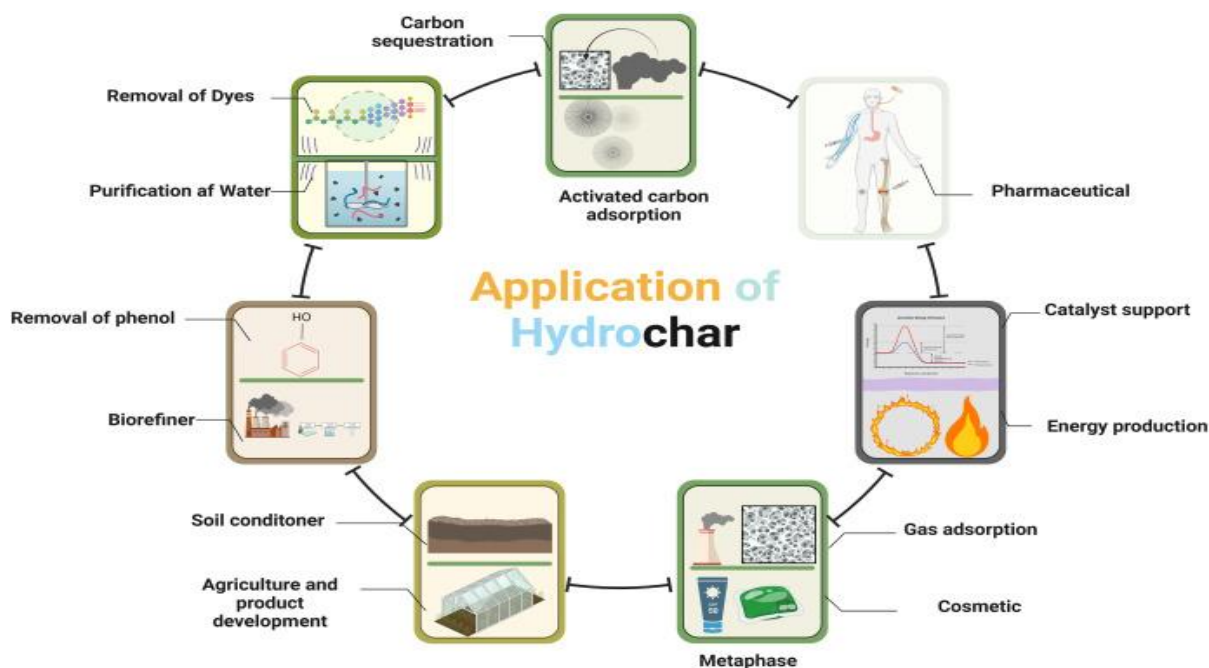


Figure 6 Application of Hydrochar

### Solid Fuel

Hydrochar is an effective solid fuel because of its high carbon content, energy density, and low ash generation. Hydrochar, produced through HTC of biomass, has qualities similar to coal but is regarded as more sustainable and environmentally benign. HTC is a proven approach for improving biomass fuel characteristics and creating new biofuels. The potential for leaching inorganic elements from the initial biomass is crucial to the HTC process. As a result, the amount of ash in the resulting hydrochars decreases (Petrović et al., 2016b; Lang et al., 2025). Solid fuels with lower ash percentage are preferred as they contain less inorganic components that can produce emissions, corrosion, clogging, fouling, and clinker formation during direct burning (Jain et al., 2015; Petrović et al., 2021). Heating biomass to 220 °C causes the devolatilization of macromolecules and the formation of more stable hydrochars. This could benefit the environment by increasing the production and usage of biomass-based products as a solid fuel (Petrović et al., 2024b).

### Adsorbent in Water Treatment

Because of its porous structure, large surface area, and abundance of surface functional groups, hydrochar is an excellent adsorbent for absorbing contaminants from aqueous solutions. Its water treatment and environmental remediation application provides an environmentally benign and cost-effective alternative to conventional adsorbents. Their structure, rich in diverse oxygenated functional groups, turned out to be ideal for surface area modification and further functionalization by various physical and chemical procedures (Petrović et al., 2024b).

### Pharmaceuticals

Hydrochar's special qualities, including its high porosity, functional surface groups, and biocompatibility, have led to its growing use in the pharmaceutical sector. It is a useful material for many pharmaceutical operations and product developments because of these qualities. Antibiotics, analgesics, antidepressants, and other personal care products are becoming increasingly problematic in many nations due to their designation as emerging organic pollutants. These compounds are commonly used to improve human and animal health and daily living. Furthermore, a considerable fraction (30% to

90%) winds up in domestic sewage via urine, feces, and baths since it cannot be absorbed by humans or animals. As a result, medications are regularly found in wastewater (J. Wang & Wang, 2016). HTC-produced hydrochars are being examined as effective adsorbents for this class of contaminants.

Table 2 Application of different hydrochars as pharmaceutical sorbents

Hydrochar	Pollutant	References
Unmodified biochar from olive oil waste	Diclofenac Ibuprofen	(Delgado-Moreno et al., 2021)
Hydrochar from olive oil waste green tea waste	Diclofenac Ibuprofen	(Yudha et al., 2019) (Algethami et al., 2024)
Phosphate-modified poplar sawdust	Ciprofloxacin	(Qin et al., 2023)
NaOH-treated sugarcane bagasse	Tetracycline	(Jais et al., 2021)
Immobilized bamboo	Paracetamol	(Senthil Kumar et al., 2024)
loquat cores	Prednisolone	(Hayoun et al., 2022)

### Soil Amendment

Biochar produced through the HTC of biomass is an effective soil amendment with significant agricultural and environmental advantages. Its porous structure improves soil fertility by boosting nutrient retention and lowering leaching, while also increasing water-holding capacity, which is especially useful in arid and drought-prone locations. This is beneficial for agricultural operations because it improves soil aeration, reduces evapotranspiration and weed pressure, maintains soil temperature, and boosts root penetration resistance (Singh et al., 2025). As a result, it is a product that is attracting increasing study attention, as its application is intended to boost agricultural yield and soil qualities (Gaskin et al., 2008). Because of the continuous loss caused by soil degradation, biochar is a remedy for the ongoing loss of organic matter (Jones et al., 2012). In recent years, biochar has been primarily promoted for three purposes: mitigating climate change by sequestering carbon, increasing crop output, and improving soil structure and functions through a variety of positive effects (Zhaoxiang et al., 2020). Furthermore, its incorporation into the soil could result in sustainable agriculture (Ayaz et al., 2021).

### CONCLUSION

Waste generation has become a global concern due to industrial activity, urbanization, and population growth, causing environmental pollution, resource depletion, and climate change. Hydrothermal carbonization (HTC) offers an efficient solution for converting wet biomass into hydrochar, a cost-effective and sustainable alternative to non-renewable carbon materials. The hydrothermal carbonization (HTC) process transforms biomass into hydrochar, with key parameters like feedstock type, temperature, and retention time significantly influencing yield and quality. Feedstock composition affects the carbon and nutrient content of the biochar. Lignin-rich biomass produces more stable, porous char, while nitrogen-rich feedstocks improve soil fertility. Temperature is critical, as higher values increase degradation efficiency and calorific value but reduce solid yield. Optimal temperatures for hydrochar production typically range between 180°C and 250°C. Retention time also impacts the reaction, with longer durations promoting more complete hydrolysis and carbonization but reducing solid recovery. This study highlights variations in yield across feedstocks. However, poplar wood achieves up to 89.9% at moderate temperatures and retention times. Shorter reaction times at moderate temperatures maximize yields, whereas prolonged times lower solid recovery. Effective temperature and reaction time tuning is crucial for balancing yield and energy efficiency across different biomass types. HTC-derived hydrochar is a carbon-rich material that has diverse applications due to its unique physical and chemical properties. As a solid fuel, it offers high carbon content, energy density, and low ash generation, making it a sustainable alternative to coal. Its porous structure and functional surface groups make it an effective adsorbent for pollutants in water treatment and pharmaceutical contaminants. Additionally, hydrochar serves as a valuable soil amendment as it enhances soil fertility, water retention, and nutrient availability while contributing to sustainable agriculture and carbon sequestration. These versatile applications underscore a great environmental and economic significance.

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