Transforming Waste Biomass through Hydrothermal Carbonization: Hydrochar Synthesis and its Environmental Benefits. A Review

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Abstract

Numerous developed nations have adopted a bio-based economy, with thermochemical conversion of municipal solid waste biomass (Bm) being the most effective method to accomplish this objective. Hydrothermal carbonization (HTC) presents a viable method for conversion of waste Bm through an environmentally sustainable process that utilizes water as reaction medium and operates at moderate temperatures (180-280 °C). HTC has effectively generated targeted carbonaceous products from diverse waste sources, including lignocellulosic Bm, sewage effluent, algae and municipal solid waste. This study examines critical HTC process parameters and chemical and physical properties of resultant hydrochar, while exploring potential conversion of modified and functionalized materials into sustainable solutions for the future.

Keywords: biomass; hydrothermal carbonization; municipal solid waste.

Introduction•

Human activities have resulted in proliferation of waste biomass (Bm) over time. Composting or disposing of waste Bm in open landfills can adversely affect environment, finances and public health. Although historically seen as waste, Bm is a valuable sustainable resource that also functions as energy source, demonstrating environmental friendliness [1]. Certain initiatives aim to enhance crude oil

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•The abbreviations list is in page 345.

production and replenish reservoirs, while others utilize greenhouse gas emissions for energy generation [2]. Waste Bm is progressively regarded as a renewable resource capable of mitigating greenhouse gas emissions [3]. Nonetheless, features such as its low energy potential and equilibrium, elevated ash content, hygroscopic biological characteristics, storage challenges and emissions produced post-combustion restrict its application. Thermochemical conversion of Bm into useful compounds has advanced considerably [4]. Heat-based technologies transform cellulose into biofuels, adsorbents and important chemicals, including bio-oil generated from alkaline compounds such as phenolic ketones, acids and furan derivatives [5]. Various techniques for carbonizing Bm have been established, including combustion, torrification, gasification by pyrolysis and hydrothermal carbonization (HTC) treatment. HTC is an effective Bm utilization technique that significantly contributes to waste treatment and solid biofuel production, being cost-effective and environmentally friendly. It functions at moderate temperatures (180-280 ºC), employing groundwater as reaction medium.

Raw materials undergo through hydrolysis, dehydration, decarboxylation, aromatization and condensation during HTC process, which is predominantly regulated by temperature and residence time (RT), affecting the structure and qualities of the result [6]. HTC has multiple advantages, such as capacity to carbonize liquid Bm prior to drying, and to diminish gas emissions resulting from oxide dissolution in processing water [7-9]. This economical and environmentally sustainable approach operates at moderate temperatures (180-280 °C), and utilizes water as catalytic medium, which serves as low-cost solvent and Bm ingredient, while being ecologically benign and non-toxic. Subcritical water functions as non-polar solvent under HTC conditions, promoting hydrolysis of organic matter molecules in Bm, and leading to rapid depolymerization into water-soluble compounds [10]. Reduced HTC temperature produces functionalized hydrochar (HC) suitable for pollution adsorption, whilst elevated temperatures generate HC with enhanced fuel characteristics. Duration of reaction exerts a comparable yet less pronounced effect on HTC's sensitivity. Extended reaction durations for hydrocarbon production give diminished outputs, but enhance aromatic complexity [11]. Carbonization and canonization in an aqueous environment generate oxygenated functional groups on solid hydrocarbon surfaces and HC [12, 13].

The method produces high-energy, coal-like hydrocarbons without gas emissions or necessity for feedstock desiccation. HTC offers advantages over conventional thermal treatments, including reduced costs and energy consumption, along with enhanced application diversity [14]. Derived solid residues exhibit significant hydrophobicity and reliability, facilitating its separation from liquids. Research demonstrates that it exceeds raw Bm in power and mass density, biodegradability and combustion efficiency as a stable fuel [15].

HC has multiple applications, including carbon sequestration, soil augmentation, bioenergy production and wastewater pollution remediation. Processing water is generated concurrently with solid HC. It may include hazardous chemical compounds and present an environmental danger, as the presence of dissolved organic matter could hinder efficient production of HC from Bm, representing a significant constraint on HTC process. Consequently, further treatment is necessary prior to the release of processing water into the environment. To surmount this obstacle, it is advisable to utilize obtained chemicals or recirculate process water to diminish water consumption during HTC [16]. This review study elucidates the influence of HTC variables on HC structure and properties, focusing on biological Bm conversion, sustainable manufacturing and potential applications for resultant materials. It underscores the significance of generating carbonaceous materials sustainably and ecologically [17].

Impact of procedural elements

Hydrocarbons produced from the same feedstock may exhibit varying physical and chemical properties based on operational parameters. Comprehending the influence of each aspect is essential for optimizing HTC processes and generating superior HC. Properties of HC are influenced by various factors, including kind and quantity of feedstock, pressure, catalyst presence, as well as primary temperature and room temperature. [18].

Thermal measurement

Temperature is a crucial determinant in defining the structure and characteristics of final products, affecting ionic and radical processes in supercritical water, as well as the extent of precursor decomposition and transformation in the energy source. Temperature variations and quantity of potentially transformed molecules significantly influence decomposition process [19]. Breakdown of lignocellulosic Bm commences at 180 °C. Extended reaction durations and elevated temperatures result in more vigorous Bm transformation reactions. Increased carbonization temperatures give more carbon-rich hydrocarbons; however, they significantly reduce solid-phase yield due to degradation [20]. Additionally, high temperatures accelerate dehydration and decarboxylation processes, leading to a decrease in oxygen concentration and modifications in both oxygen-to-carbon and hydrogen-to-carbon atomic ratios in cellulose. The process produces HC with enhanced fuel properties, particularly when variations occur in higher and lower heating values (HHV and LHV) [21]. Numerous studies have examined the impact of this method's component. As deterioration occurs across diverse climates, each bioenergy component is affected differently by HTC. Plant matter precursors are generally transformed into solid hydrocarbons at temperatures from 180 to 280 ºC. In selecting Bm, it is important to consider carbonization and temperature. Elevated process temperatures led to Bm degradation, which results in diminished HC generation, volatile matter, and O content, while increasing its fixed carbon content (FCC) and heat equilibrium [22]. Inorganic components at outset significantly affect product´s qualities. Thermal treatment over 180 ºC eliminates inorganic compounds from Bm. Additional research has demonstrated that HTC treatment of municipal solid waste food at temperatures from 180 to260 ºC can yield renewable energy [23]. At 260 ºC, HHV produced highest overall fluid catalytic cracking yield, but lowest mass production. Peak rate of consistent biofuel production was achieved at 180 °C. Experts have concluded that 225 °C is the most reliable temperature for a specific energy supply. Other researchers have obtained similar findings about the influence of temperature on hydrocarbon characteristics, such as energy potential, porosity and re-adsorption capacity of grape pomace and *Miscanthus x giganteus* HC, while concurrently reducing volatiles, ashes and moisture content [24].

Dissolution of organic matter has been assessed in HC produced from cow dung, maize stalk and *Myriophyllum aquaticum* at three specific temperatures (180, 200, and 220 °C). Researchers found that elevating HTC temperature reduced dissolved organic carbon content from HC, enhanced aromatic content and transpiration of cow dung HC, and affected dissolved organic matter [25]. Nonetheless, it adversely affected cornstalk and HC.

Elevated pressure

Tension is generated during HTC management, primarily influenced by initiation of Bm and carbonation temperatures. This variable exerts no meaningful influence on the procedure itself. Autogenic pressure increases with rising reaction temperature. Comprehending the pressure generated from feedstock-water interactions is essential for constructing safe and economical equipment [26, 27]. Pressure levels fluctuate based on feedstock type, initial ratios, reaction temperatures and RT. In pressured HTC systems, chemical decomposition of materials results in formation of solid hydrocarbons, which consist of water, simple organic compounds and gases [28]. Pressure at reaction temperature is affected by saturated water vapor pressure, partially soluble gases produced during HTC processes and inert non-soluble gases (e.g., N) introduced into a pre-pressurized system [29]. Carbon dioxide is the most abundant gaseous byproduct, and its concentration affects factors that lead to increased pressure. While temperature is a secondary factor, certain studies examine its impact on HTC procedures, and have found that elevating it to 250 ºC, and boosting pressure to 50 or 240 bar, improves feedstock conversion into hydrocarbons. Degree of structural change fluctuates according to feedstock composition.

It has been discovered by [30], in their Brunauer-Emmett-Teller experiment, that raising pressure during HTC process reduced surface area of Maize shell hydrocarbons from 7.4 to 4.8 m²/g. HHV of effluent hydrocarbons diminished from 8.0 to about 6.5 MJ/kg, as pressure escalated from 0.1-0.9 to 3.1-5.4 MPa, notwithstanding improved effectiveness of dewatering processes. Therefore, temperature and pressure exert a more significant influence on hemicellulose-cellulose Bm structures than on cellulose-lignin structures [31]

Residence time

A study by [32] revealed that extended RT accelerates the process, diminishes solid regeneration and generates enduring hydrocarbons with a polyaromatic structure. Synthesis of secondary HC in lignocellulosic Bm is contingent upon time, while temperature exerts a more significant influence on non-dissolved monomers. Elevated RT enhances HC synthesis, and produces a greater quantity of intermediate compounds. Characteristics of HC derived from Water hyacinth are affected by RT. Decreased RT led to fissures on HC's surface, whereas spheres formed after around 6 h.

According to [33], polymerization and hydrolysis are regulated by RT. Microspheres aggregated after 24 h, leading to diverse HC textures. Dimensions of nanoparticles were also affected by room temperature. Results demonstrate that temperature exerts a more significant influence on HC characteristics than RT. Extending RT from 60 to 180 min, at 200 °C, during carbonization of Banana stems has reduced hydrocarbon production from 61.8 to 57.8% [34]. Nonetheless, both HHV and FCC content had a significant rise, from 18.7 to 18.9 MJ/kg and from 35.0 to 44.3%, respectively. Increasing process temperature from 160 to 200 ºC (180 min) resulted in a yield reduction from 72.8 to 57.8%, while enhancing HHV and preserving FCC from 18.4 to 18.9 MJ/kg, and from 22.5 to 44.3%, respectively. Needed RT to polymerize produced hydrocarbons to a specified extent has been established by [35].

Catalysts

Inorganic and organic catalysts can expedite chemical reactions during thermal carbonization, and improve hydrocarbon properties. Inclusion decreases reaction temperature, enhances hydrolysis, facilitates denitrogenation and deoxygenation, increases hydrocarbon yield, and functionalizes produced hydrocarbons [36]. Natural fertilizer catalysts, such as acids and alcohols, can initiate or accelerate chemical processes. Natural acids decompose water, generating neutral solvents that accelerate reaction rates.

Citric acids, a safe and economical acidic catalyst, improve Bm conversions during HTC process by degrading bio-polymers. This promotes HC formation and elevates material content. Increasing concentration of citric acid from 0.1 to 0.5 M post-HTC resulted in enhanced FCT and HC in dewatered waste-activated drainage [37].

Carbonization of material with citric acid may lead to formation of other acids, such as formic or acetic acids, which engage with minerals, thus influencing hydrolysis dehydration process [38].

Acidic circumstances can yield functional chemicals that strengthen cellulose framework and remove elements and organic groups from Bm supply, leading to coarser and more porous structures. Reports indicate that employing acidic conditions in HTC process with cellulose microfibers derived from softwood pulp enhanced diameter of C spheres [39]. Employing citric acid as catalyst facilitates degradation of cellulose, yielding soluble oligomers and glucose. Molecules undergo dehydration, compaction and polymerization, to yield C spheres.

Acetic acid influences hydrocarbon properties and HTC process. This catalyst has enhanced thermal stability and FCC, while generating fewer hydrocarbons compared to alternative catalysts. Structure of citric acid enhances carbon content during HTC, and its acidic properties promote dissolution of organic molecules in substrates more effectively than acetic acid. Consequently, acids may be more effective in diminishing yield via fragmentation reactions than in promoting polymerization [40].

Protic solvents, like methanol and ethanol, form hydrogen bonds with electronegative molecules, such as oxygen and nitrogen. Hydrogen bonding and donation can augment hydrocarbon production from high-protein and carbohydrate feedstocks [41]. Incorporation of artificial acidic reagents enhances hydrocarbon properties by leaching organic molecules, establishing acidic mineral conditions, eliminating ash and depolymerizing cellulose, thus improving hydrolysis and dehydration processes.

Inorganic catalysts consist of robust mineral bases and acids, aluminum chlorides, sulfate and nitrate salts, iron oxides and hydrogen peroxide [42]. Strong acids in minerals enhance fuel properties and nutrient release of HC. This leads to enhanced porosity and reduced volatile material concentration during HTC, hence improving the hydrate’s stability. Sulfuric acid has been investigated as catalyst for carbonization of sewage sludge, with findings indicating that its addition significantly enhances specific surface area, facilitating feedstock decomposition and conversion. The use of a catalyst facilitated immigration of elements, leading to elevated concentrations of Cu, Zn and ZnO in HC, while concurrently reducing quantities of Cr and Ni compounds [43]. Post-processing water contained elevated concentrations of P, Ca, Mg and Zn. A robust mineral foundation, such as CaO, enhances hydrocarbon production and ash concentration, while diminishing organic matter, particularly polycyclic aromatic hydrocarbons [44]. Sodium hydroxide can mitigate sulfur dioxide and nitrogen oxides emitted by hydrocarbon combustion, while improving moisture diffusivity. Metal chlorides alter structure and surface characteristics of HC, lower activation conditions, accelerate dehydration, and enhance thermal escalation alongside burning of solids [45]. The study indicates that type of material and HTC frequency significantly influence HC characteristics. Optimizing procedures for particular applications necessitates considering precursor Bm and final utilization [46].

Environmental applications for hydrocarbons

Fossil fuel

Numerous wealthy countries aiming for a bio-based economy seek to harness wasted Bm as sustainable energy source and feedstock for biofuel production. HTC is an established method for enhancing Bm fuel properties and developing novel biofuels [47]. HC surpasses untreated wood in fuel quality, exhibiting greater FCC's total energy density, reduced ash and volatile content, enhanced reactivity, improved dewaterability and superior material robustness. Generated HC possesses characteristics comparable or superior to those of commercial coal and lignite. HTC technique facilitates leaching of inorganic compounds from original Bm, hence diminishing ash content in hydrocarbon fuels. Carbonizing grape juice at 200 ºC decreased ash percentage in HC from 6.48 to 3.55%. This resulted from total absorption of inorganic minerals (K, Mg, Ca, Si and P) during water processing [48]. A reduced ash percentage is essential for solid fuels, since elevated levels of organic constituents (Si, K, Na, S, chlorine, P, Ca, Mg and Fe) in fuels, in conjunction with Bm, can lead to emissions, oxidation, clogging, contaminants and clinkers in combustors during direct combustion process [49]. These problems result in increased maintenance expenses and diminished fuel efficiency. Bm is more volatile than coal, resulting in inefficient combustion and increased greenhouse gas emissions. Research by [50] indicates that HTC can reduce volatile content of waste biomass [51]. This study has shown that heating urban materials at 180 °C rose volatile chemicals from 80.7 to 82.2%. Lignocellulose starts hydrolysis at 180 ºC, which has astonished researchers. Leached volatile chemicals from treated water can accumulate on hydrocarbon substrates. Aromatic adsorption was notably significant during HTC procedures on sludge at 180 °C. An elevated HTC temperature has diminished HC's peak, which refers to breakdown rate.

Research indicates that heating wood to 220 ºC leads to devolatilization of macromolecules and creation of stable hydrocarbons. This could benefit the environment by enhancing production and utilization of Bm-based products, including solid energy sources [52]. Fragments undergo degradation through dehydration, decarboxylation and aromatization, resulting in a carbon-rich solid. Concurrent breakdown activities in HTC yield HC with reduced volatile content were similar to those of comparable Bm [53]. Hydrocarbon as bio-energy offers benefits compared to traditional petroleum and Bm, such as HHV and LHV. These attributes render them appropriate for applications beyond fuel. Temperature is once more the primary determinant of these parameters. A study by [54] has indicated that HTC treatment with *Miscanthus*, wool stem and Paulownia leaves resulted in increases of 58 and 65% in HHV and LHV, respectively, compared to pure mushroom media.

Adsorbents for contaminants in liquid solutions

HC possesses the capability to eliminate pollutants from water, among other uses. Presence of oxygenated groups in the structure rendered it appropriate for future functionalization and surface area modification using physical and chemical techniques. Various modification techniques, such as alkaline agents (KOH and NaOH), acids (H3PO4 and HCl), metallic salts (ZnCl2, MgCl and K2CO3) and polymerization processes have been employed [55]. KOH, a prevalent activator, cleanses partially obstructed pores while simultaneously introducing newly generated ions to HC surfaces. Alkaline treatment increases surface area by eliminating organic particles from HC, but acidic method modifies mesoporous structure. Proposed solutions involve incorporating functional structures into HC surfaces and altering sorbent materials to create tailored structures, hence enhancing efficacy in removal of diverse contaminants [56].

Heavy metal contamination in industrial water poses a significant risk to environmental integrity and human health. Contaminants include mercury, lead, inorganic dyes, pesticides and other natural substances discharged into river watercourses, which elicit significant concerns. Pollutants originate from agricultural and mining effluents, encompassing those from textile, servicing, paper, leather, tanning and feeding industries [57]. Harmful and non-recyclable pollutants build in tissues of plants, animals and humans, ultimately impairing their neurological, liver and reproductive systems, and leading to diseases such as dermatitis, cancer and renal failure. It is essential to devise efficient and economical techniques for removal of metals, including mercury, and other pollutants from industrial effluents prior to their discharge into waterways. Novel sorbents sourced from renewable materials, such as HC, are under investigation to enhance traditional purification methods [58]. HC possesses restricted surface area and porosity, yet its chemically active functional groups (ketones and carboxylic acid groups, especially hydroxyl) facilitate effective adsorption.

Numerous studies have demonstrated that HC sourced from diverse precursors can efficiently eliminate metallic elements from aqueous solutions [59]. Moreover, various modification strategies have been employed to enhance capacity for certain pollutants. A study by [60] has determined that phosphate-modified Aspen sawdust HC may function as adsorbent for Pb(II) ions. FTIR analysis indicated that surface compounds eliminated Pb(II) through phosphorus-containing groups, while aromatic structures engaged with cations via π interactions. -COOH group of P-HC exhibited superior efficacy in adsorbing Pb(II) compared to -OH group. Pb(II) ions exhibited adsorption capacity of 119.61 mg/g, with primary mechanisms including precipitation, π-π interactions and complexation. KOH-modified grape seeds' HC eliminated five times more lead (137 mg/g) compared to unmodified grape pomace HC (27.8 mg/g) as evidenced by [61]. The work by [62] indicated that alkaline modification resulted in structural alterations, including incorporation of O-rich functional groups within its hydrocarbon matrix, adsorption of K+ ions for ion exchange with elements such as lead, and remediation of partially obstructed pores. As demonstrated by [61], structural changes enhanced Pb2+ adsorption by establishing more robust binding sites. Adsorption of specific ions was achieved through ion exchange, utilizing a combination of chemicals and Pb(II)-π interactions, with Sips isotherm model demonstrating most accurate fit to experimental data.

Mn(II) ions were neutralized utilizing a magnetized HC composite derived from pineapple leaves [63]. High capacity of magnetic Watermelon seeds has been shown to efficiently eliminate Cd(II) ions from liquids. Application of NaOH to modify HC with Ca-doped wasted mushroom substrate has yielded highly efficient sorbents for removal of Pb(II) ions. Binding may occur through intricate Pb-π electron interactions. An N-doped hydrocarbon derived from corncob was utilized to concurrently remove Cu(II) and Cr(VI) ions, contributing to environmental sustainability [64].

Alteration of NH_4Cl enhanced adsorption of Cu(II) and Cr(VI) to 1.223 and 1.995 mmol/g, respectively, in comparison to unmodified HC. Infrared spectrum indicated that notable redox processes augmented the number of imine-type protons on the surface of N-doped HC, possibly creating additional Cu(II) binding sites. At pH levels below point of zero charge, n-plated HC exhibited a greater affinity for resorption of Cr(VI) compared to Cu(II), attributed to electrostatic attraction [65]. A hybridized amino-modified wood benzene was synthesized by combining the molecule with acryloyl chloride, amines, and hydrochloric acid, which was later employed to adsorb Cr(VI) ions. Researchers have shown that incorporating amine groups onto HC surfaces markedly enhanced adsorption capacity (523.57 mg/g) by neutralizing pollutants via electrostatic interactions [66].

A cost-effective sawdust hydrocarbon composite (MgSi-HC) was utilized for removal of Cu(II) and Zn(II). MgSi-HC possesses an extensive, precise contact area and clearly delineated pore structure. Adsorption equilibrium values reached a maximum values of 214.7 and 227.3 mg/g, for Cu(II) and Zn(II), respectively. Adsorption is thought to involve interactions among electrostatic hydrogen bonds, π-π stacking interactions and pore filling.

Composite HC obtained from residual mushroom substrate has been evaluated for its efficacy in removing Pb(II) and Cd(II) ions from water. Freundlich's isotherm experiment demonstrated that Ca-modified HC displayed maximum sorption capacities of 297 and 131 mg/g for Pb(II) and Cd(II), respectively. Binding encompassed ion exchange, epidermal complexation, mineral precipitation and cation-π association [67].

Colorants

Dyes, along with heavy metals, are a prevalent cause of industrial pollution, as they are highly toxic, carcinogenic and non-biodegradable, even at minimal concentrations, presenting a significant threat to all forms of life. Synthetic dyes utilized in textile industry can impact aquatic organisms by contaminating water sources and infiltrating their food chain. To mitigate environmental pollution, industrial water must be treated to eliminate contaminants and colors prior to release [68]. Prior research has demonstrated that HC can adsorb these chemicals from aqueous environments. A study conducted by [69] on HTC of HC (HC) derived from olive waste at 250 ºC evaluated its efficacy in removing methylene blue (MB) utilizing Congo red. NMR analysis elucidated the structure of HC. The presence of carbonyl and carboxylic groups on HC surface led to practically total dye elimination within 120 and 180 min, respectively. Elimination of MB was investigated utilizing ozone-treated pine tree HC and $KHCO_3$-modified hydrocarbons derived from industrial laundry sludge [70].

A study by [71] revealed that magnetized watermelon seeds grafted with HC-chitosan effectively absorbed brilliant green mineral malachite. Ideal circumstances for attaining a permeability of 420.02 mg/g were pH of 7.5, duration of 420 min and 20 mg adsorbent dosage at 298 K. Integration of bimetallic organic framework (NiFe-MOF) into bagasse with sugar cane HC resulted in dual 3-D structure featuring multiple functional groups and an extraordinarily high removal rate of crystal lavender dye (395.9 mg/g)[72]. The modification produced a material with double the surface area, increased carboxylic and metal-carboxylate structures, enhanced thermal stability and improved chemisorption adsorption. Similarly, crystal violet was absorbed utilizing NaOH-activated bagasse residues from sugar HC. Cold potash treatment enhanced performance of oxygenated cell groups and increased material porosity by removing pore blockages.

Research [73] indicates that cationic elimination of dye entails electromagnetic attraction between introduced MB amino acids, negatively charged functional groups on hydrocarbon surfaces, formation of hydrogen bonds, π-π dispersion interactions between aromatic hydrocarbon structures and MB rings, surface complexation processes and ion exchange among components.

Antibiotics and personal care products, including analgesics and antidepressants, are categorized as emerging organic pollutants, raising concerns in multiple countries[73]. Despite prevalent usage of these compounds to enhance humans and animals health, a significant proportion (30% to 90%) is excreted into residential sewage via urine, feces and bathing, as they are indigestible. Consequently, since medicines are often detected in wastewater, they must be eradicated to prevent detrimental consequences[74]. Diverse approaches have been employed for this objective, including precipitation, barrier separation and adsorption. HC from HTC method is currently undergoing evaluation for its efficacy as adsorbent for this category of pollutants[74].

Conclusion

HTC is an effective thermochemical process that transforms plant materials into valuable products such as HC, applicable in various domains, including solid biofuels that adsorb, absorb and store intermediates, as well as facilitate soil cleanup and conditioning. HC functions variably based on its chemical, chemical-derived and structural characteristics. Its highly changeable surface allows for customization for various uses. To enhance utilization of HC as sorbent in extensive applications, it is crucial to comprehend methods for modifying its surface and facilitating its regeneration. Significant advancements have been made in comprehending hydrological conversion process, encompassing production mechanisms of HC its their fundamental structural characteristics. This work has emphasized characteristics of HT process, including pressure, temperature, RT and catalysts, along with methods for tailoring its surfaces for environmental applications.

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Authors' contributions

M. Asif: improved manuscript and corrected grammar mistakes. **M. Shoaib**: helped with figures, tables and the manuscript. **N. A. Khan**: rechecked the whole paper. **H. M. B. Munir**: setting of references and dois. **M. Siddique**: improved abstract and conclusion**. S. K. Suri**: removed mistakes in the manuscript; solved plagiarism. **M. M. Memon**: corrected and checked the manuscript. **B. Ali**: rechecked the whole manuscript. **S. Afzal**: removed errors, formatted manuscript.

Abbreviations

Bm: biomass
FCC: fixed carbon content
HC: hydrochar
HHV: higher heating value
HT: hydrothermal
HTC: hydrothermal carbonization
KOH: potassium hydroxide
LHV: lower heating value
NaCl: sodium chloride
RT: residence time
T: temperature

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