frontiers | Frontiers in Chemical Engineering

MINI REVIEW
published: 07 April 2022
doi: 10.3389/fceng.2022.867228

Hydrochar: A Promising Step Towards Achieving a Circular Economy and Sustainable Development Goals

Lokesh P. Padhye[1]*, Erick R. Bandala[2], Buddhi Wijesiri[3], Ashantha Goonetilleke[3] and Nanthi Bolan[4,5]

[1]Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand, [2]Division of Hydrologic Sciences, Desert Research Institute, Las Vegas, NV, United States, [3]School of Civil and Environmental Engineering, Queensland University of Technology (QUT), Brisbane, QLD, Australia, [4]School of Agriculture and Environment, The University of Western Australia, Perth, WA, Australia, [5]The UWA Institute of Agriculture, The University of Western Australia, Perth, WA, Australia

The United Nations 17 Sustainable Development Goals (SDGs) are a universal call to action to end poverty, protect the environment, and improve the lives and prospects of everyone on this planet. However, progress on SDGs is currently lagging behind its 2030 target. The availability of water of adequate quality and quantity is considered as one of the most significant challenges in reaching that target. The concept of the 'Circular Economy' has been termed as a potential solution to fasten the rate of progress in achieving SDGs. One of the promising engineering solutions with applications in water treatment and promoting the concept of the circular economy is hydrochar. Compared to biochar, hydrochar research is still in its infancy in terms of optimization of production processes, custom design for specific applications, and knowledge of its water treatment potential. In this context, this paper critically reviews the role of hydrochar in contributing to achieving the SDGs and promoting a circular economy through water treatment and incorporating a waste-to-value approach. Additionally, key knowledge gaps in the production and utilization of engineered hydrochar are identified, and possible strategies are suggested to further enhance its water remediation potential and circular economy in the context of better natural resource management using hydrochar. Research on converting different waste biomass to valuable hydrochar based products need further development and optimization of parameters to fulfil its potential. Critical knowledge gaps also exist in the area of utilizing hydrochar for large-scale drinking water treatment to address SDG-6.

Keywords: hydrochar, water quality, sustainability, sustainable development goals, circular economy

Edited by:
Kevin M. Van Geem, Ghent University, Belgium

Reviewed by:
Chao He, Tampere University, Finland

***Correspondence:**
Lokesh P. Padhye
l.padhye@auckland.ac.nz

Specialty section:
This article was submitted to Sustainable Process Engineering, a section of the journal Frontiers in Chemical Engineering

Received: *31 January 2022*
Accepted: *07 March 2022*
Published: *07 April 2022*

Citation:
Padhye LP, Bandala ER, Wijesiri B, Goonetilleke A and Bolan N (2022) Hydrochar: A Promising Step Towards Achieving a Circular Economy and Sustainable Development Goals. Front. Chem. Eng. 4:867228. doi: 10.3389/fceng.2022.867228

INTRODUCTION

The United Nations 17 Sustainable Development Goals (SDGs) are intended to ensure peace and prosperity for people and safeguard the natural environment from human-induced pollution and climate change (UNDESA, 2018). SDGs progress, however, is currently lagging behind its stipulated 2030 target because of continued environmental degradation, increasing social problems such as poverty, inequality and inequity, and financial and economic instability (Jackson, 2009; Banerjee et al., 2011; Sachs, 2015). While all the proposed SDGs are equally important and of high priority, the first and central SDG of "No Poverty" is strongly linked to water (Merrey, 2015). Water permeates all aspects of our daily lives as the availability of water of adequate quality and quantity is not only

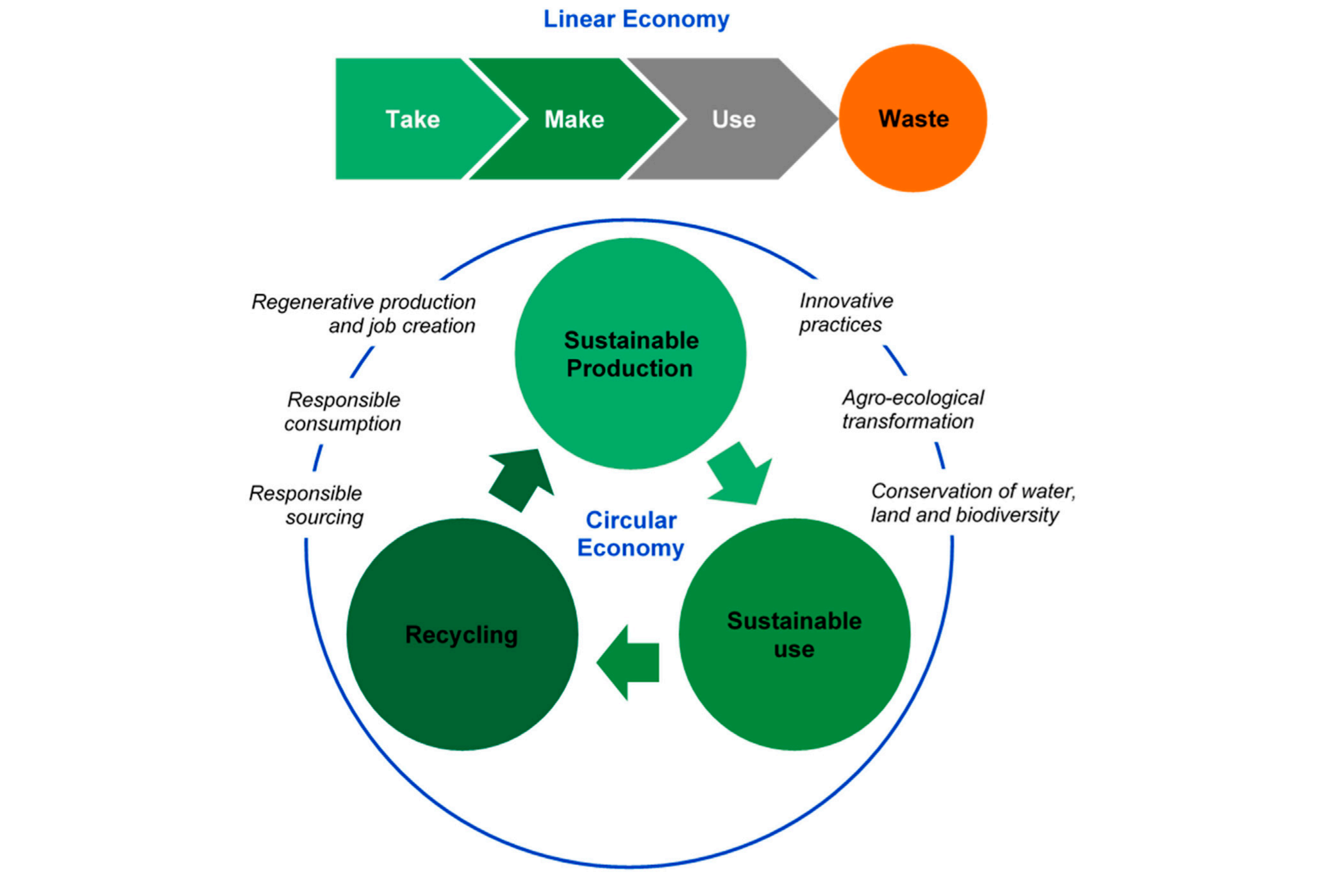

FIGURE 1 | Illustration of the concepts of linear and circular economies.

essential for the survival of humans but also for maintaining healthy ecosystems, including agroecosystems, which in turn translates to community wellbeing. Good water quality can promote healthy lives, while degraded water quality will adversely impact human wellbeing and economic development. In addition, multiple interdependencies involving water as a key natural resource, such as water-food-energy nexus, highlights its role in the sustainable development framework. Hence, availability of clean water has been termed as a "critical entry point" to achieve sustainable development and nearly all of the proposed SDGs (Merrey, 2015).

In recent years, the concept of the "Circular Economy" has gained increasing attention with the hope of overcoming some of the intractable sustainability challenges (Ghisellini et al., 2016). The classical linear economic system utilizes natural resources and non-renewable energy to produce goods and services, which eventually generate mostly non-biodegradable waste. On the other hand, the circular economy is based on the concepts of conservation, reuse, and recycling to produce goods and services, as illustrated in **Figure 1**. More formally, "the circular economy" is defined by Geissdoerfer et al. (2017) as *"a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops"*. In this context, a circular economy is relevant to all sectors of the economy, including energy, materials, industry, health care, financial and information technology, and can be a driver for accelerating progress in achieving SDGs (UNGA, 2019).

One of the more promising solutions that have emerged in recent decades to close the materials and energy loops mentioned above is the conversion of waste biomass to biofuels. It can be achieved either through thermochemical or biochemical conversion processes. Out of these two alternatives, thermochemical processes are being widely explored due to inefficiencies and practical difficulties associated with biochemical processes (Tripathi et al., 2016). Pyrolysis is the most commonly used thermochemical process and is carried out at temperatures higher than 300°C and in the absence of oxygen. The solid output of this process is called 'biochar', which has been extensively discussed in the literature for its environmental, agricultural, and material applications (Bolan et al., 2021). Due to the higher energy input required for pyrolysis and expensive pretreatment needs, hydrothermal carbonization (HTC) has replaced pyrolysis as the preferred thermochemical process for some waste biomass, especially those with high moisture content. HTC is carried out at relatively lower temperatures, typically from 80 to 240°C, under subcritical water pressure (Nadarajah et al., 2021). The solid output of this process is called "hydrochar".

Hydrochar is gaining popularity as an environmentally and economically sustainable material with multiple applications, including as an effective adsorbent to remediate polluted water. Hydrochar can be produced using a range of widely available biomass, including agricultural waste, sewage sludge, manure, and microalgae through HTC, which ensures sustainability in raw materials sourcing, energy consumption, and waste management (Nadarajah et al., 2021). However, compared to biochar, hydrochar is still in the early stages in terms of optimization of production processes, custom design for specific applications, and knowledge of pollutant removal processes. In this context, this paper examines the role of hydrochar in contributing to achieving the relevant SDGs and promoting a circular economy through water quality remediation and incorporating a waste-to-value approach. Additionally, some of the knowledge gaps in the production and utilization of engineered hydrochar are identified, and possible strategies are suggested to further enhance the circular economy in the context of better natural resource management using hydrochar.

HYDROCHAR AND WATER QUALITY

Only one out of the 17 UN SDGs focuses explicitly on water, "SDG 6—clean water and sanitation for all". However, water is also an enabler to achieving the other 16 SDGs. There is also growing recognition of the multiple interdependencies or "nexus" among the various SDGs, including water and energy, water and food, water and environment, or water and economy. Hence, addressing the growing water scarcity and quality challenges is critical to achieving UN SDGs by 2030 (Merrey, 2015). Unfortunately, the latest United Nations data on SDG 6 (UNDESA, 2020; UN_Water, 2020) indicate very concerning trends in the provision of safely managed drinking water resources and sanitation services across the world. The data show that the proportion of the urban population using safely managed drinking water services exhibits a slightly decreasing trend over time (86.2% in 2000; 85.9% in 2010; 85.2% in 2017). Essentially, safe drinking water provision is not meeting the growing demand of the ever-increasing urban population. Similarly, in rural areas, the availability of contaminant-free safe water has shown only a slight improvement. It remains behind target, with nearly half of the total population not having access to contaminant-free freshwater sources. These findings need to be viewed in the context that the urban population is increasing whilst the rural population is decreasing in all countries around the world. More strikingly, the proportion of the global population using drinking water free of contamination shows an increase of only four percentage points over the five years (2015-2020) since the adoption of SDGs. To meet the target set out for SDG 6 by 2030, the rate of progress in achieving quality clean water resources needs to be more than triple for the remaining years (Ritchie and Roser, 2021). Hence, developing sustainable and inexpensive water treatment solutions is the need of the hour.

It is where hydrochar, as an inexpensive material because of the abundance of waste biomass (e.g., agriculture, forestry, food, and wastewater treatment) and less energy-intensive HTC process, can play a key role. As a result of hydrolysis and biomass monomer reactions during HTC, hydrochar surface hosts various chemically reactive functional groups, including acidic surface functional groups, that can drive the adsorption of contaminants through electrostatic interactions (Sumaraj et al., 2020). However, HTC alone produces hydrochar with low surface area, and hence, it may need to be combined with additional activation steps to increase its porosity and surface area desired for certain environmental remediation purposes (Tasca et al., 2019). The physicochemical properties of contaminants and the surface chemistry of adsorbents control the chemisorption of water contaminants (Sumaraj and Padhye, 2017). Typical functional groups on hydrochar can be optimized for increasing their adsorptive capacity or removing selective contaminants. It can be effectively achieved by altering physicochemical properties with additional activation steps (Peng et al., 2019; Teng et al., 2020; Çatlıoğlu et al., 2020; Mittapalli et al., 2021).

Although most studies have reported specific techniques for optimizing surface functionality of hydrochar for efficient adsorption of contaminants, a significant knowledge gap exists in relation to their real-world application. For example, recent studies by Zhang et al. (2022) and Lv et al. (2022) have reported methods to make hydrochar surfaces more positively- and negatively charged, respectively, for higher adsorption of anionic and cationic contaminants in wastewater. Both studies claim that their modified hydrochars could be used for wastewater treatment, but neither of these studies used actual wastewater in their batch experiments. The lack of consideration given to various parameters/factors, including complex aqueous matrices, continuous flow reactors, large-scale setups, competition by solutes for active sites in the presence of organic matter, and data related to regeneration efficiencies for real-world applications, make such claims questionable. Even if the surface modifications show promising results in the batch-scale studies, more *in situ* or field measurements should be conducted on a longer-term to examine the changes in surface chemistry and adsorption performance of chemically modified hydrochars in complex environments.

For the removal of uncharged or nonpolar contaminants, hydrochars need morphological and/or chemical modifications to achieve efficient adsorption. Although hydrochars have typically low surface area, with the help of chemical activation, surface areas higher than 1,000 m^2/g, similar to activated carbons, have been reported (Zhu et al., 2015; Zhang et al., 2019). The activation of hydrochar by KOH, NaOH, K_2CO_3, H_3PO_4, $ZnCl_2$ and other acids, bases, salts, and oxidizing agents have been reported in the literature to increase their surface areas significantly (Zhu et al., 2015). Lower peak temperatures and lower residence times of the HTC process have been reported to enhance surface area; thus, effective activation achieved at these conditions can result in hydrochars with higher surface areas and surface reactivity (Fang et al., 2015; Zhu et al., 2015). However, most of the reported research on activation of hydrochar has solely focussed on surface area enhancement, while little or no information is available regarding the cost and energy input for

TABLE 1 | Selected studies on aqueous contaminant removal using hydrochar.

Target Contaminant	The Feedstock Used for Hydrochar Production	Key Findings	References
Dyes	Food waste	Dye adsorption was spontaneous and endothermic; van der Waals forces, electrostatic interactions, and hydrogen bonding are three proposed mechanisms	Parshetti et al. (2014)
Dyes	Sewage sludge and further activation	High adsorption was attributed to strong p-p stacking interaction and electrostatic attraction	Liu et al. (2017)
Dyes	Bamboo and acrylic acid in the presence of ammonium persulphate	High adsorption was attributed to electrostatic interactions of methylene blue with carboxylate-rich surface of hydrochar	Lv et al. (2022)
Organic Matter	Fibers from wastewater screenings and further activation	Hydrochar surface area was found to be higher than commercial activated carbon, but the removal of organic matter was lower. Researchers claimed that screened fibers provide all carbon required for wastewater treatment	Benstoem et al. (2018)
Lead	Pinewood and rice husk	Lead adsorption was strongly influenced by pH. O-containing surface functional groups were found responsible for higher adsorption	Liu and Zhang, (2009)
Uranium	Switchgrass	Fast Uranium adsorption followed the H-type isotherm. The adsorption mechanism was related to the contaminant's pH-dependent aqueous speciation	Kumar et al. (2011)
Copper and Cadmium	Switchgrass and further activation	Activated hydrochar showed higher adsorption capacity than powdered activated carbon (PAC) because of hydrochar's O-containing surface functional groups	Regmi et al. (2012)
Hexavalent chromium	Bamboo	Cation functionalized hydrochar bearing—N^+H_2R was found to electrostatically attract Cr(VI) under acidic conditions and reduce it to Cr(III)	Zhang et al. (2022)
Tetracycline	*Salix psammophila* and further activation	One step activated hydrochar produced magnetic porous carbon with improved surface area	Zhu et al. (2014)
Triclosan, ibuprofen, diclofenac	Olive oil production waste	Phenolic compounds on the surface were found to play an important role in the sorption mechanisms of the studied compounds on hydrochar	Delgado-Moreno et al. (2021)

such activation at large scale. Weight ratios of activating agents: hydrochar have been reported as high as 1:1 (Zhu et al., 2015; Zhang et al., 2019), which can make their large scale applications economically unfeasible. Hence, there exists a significant research gap on cost-benefit analysis and scaling-up of activation processes.

The presence of contaminants, including potentially toxic elements in the feedstock, is another concern in relation to hydrochar application for water remediation. For example, wastewater sludge may contain toxicants and, when used as a feedstock, can lead to the leaching of these contaminants from sludge-derived hydrochars during their applications to treat water. In such cases, specific inexpensive pre- or post- HTC treatments can significantly lower the concentrations of residual contaminants (Hoang et al., 2022). However, ecotoxicological risks posed by the use of such hydrochars are rarely investigated. Consequently, in-depth studies are needed to understand the toxicological risks of using sludge-derived hydrochars for extended periods of water treatment.

As shown in **Table 1**, most of the research on hydrochar for water remediation has focused on removing dyes, heavy metals, and pharmaceuticals. There is a need for more studies on understanding the interactions of hydrochars with pollutants commonly found in urban and/or agricultural runoffs, wastewaters, and surface waters such as inorganic nitrogen contaminants, phosphorus, and emerging contaminants. Especially with the increasing number of studies reporting the presence of poly- and perfluoroalkyl substances (Lenka et al., 2022), personal care products (Kumar et al., 2019a), illicit drugs (Kumar et al., 2019b), and disinfection by-products, such as *N*-nitrosodimethylamine (Jasemizad et al., 2021), in urban waters, it is critical that the hydrochar's applicability for water treatment should consider its performance against modern-day contaminants.

HYDROCHAR AND CIRCULAR ECONOMY

Agricultural residues are increasingly being used as a sustainable source of energy in rural areas (Mau and Gross, 2018; Huang et al., 2019). As such, hydrochar production using agricultural residues in rural areas would provide additional economic benefits by integrating renewable energy, water treatment, and waste management. Similarly, sewage sludge and food waste are increasingly generated in urban areas due to the increasing population, where their use for hydrochar production can yield multiple benefits, as described above (Tasca et al., 2019). In fact, urban-produced wastes are often found to cause air, water, and soil pollution while, at the same time, cities account for 75% of global greenhouse gas emissions (Van Hullebusch et al., 2021). Hence, using these wastes for generating value-added products for various sustainable applications is a prime example of a circular economy in action. Hydrochar production is a promising pathway to support the transition to a circular economy by adding innovation to most basic services, such as water and wastewater services, waste materials management, energy production, construction materials etc., in big cities and small towns (Zvimba et al., 2021). **Table 2** lists examples

TABLE 2 | Hydrochar production and its applications in line with principles of circular economy.

Production/Application	TRL[a]	General Information	References
Hydrochar production from sewage sludge	3	The influence of alkali and inorganic and organic acids as additives for phosphorus removal, heating value and yield of produced hydrochar was assessed	Ekanthalu et al. (2021)
Hydrochar production from municipal solid waste	3	Machine learning tools were used for bridging inputs and outputs to predict hydrochar properties and develop hydrochar production optimization	Li et al. (2021)
Hydrochar production from municipal solid waste	3	Catalytic hydrochars were produced for testing the influence of treatment time, compost load, and temperature	(Magdziarz et al., 2021; Roman et al., 2021)
Use of HTC to improve sewage sludge dewatering and produce high heating value hydrochar	2	Sewage sludge co-carbonized with different biomass wastes. The use of additives suggested HTC improved dewaterability and provided optimal fuel properties	Wilk et al. (2021)
Hydrochar from different feedstocks evaluated for carbon capture and storage	2	Best performance achieved for hydrothermal treatment-carbon capture and storage of lignocellulosic biomass at low temperature	(Cheng et al., 2020; Gallucci et al., 2020)
Hydrochar as bio-asphalt modifier	3	Hydrochar-modified asphalt showed better performance compared to unmodified asphalt. The optimized dosage was 6 wt% with Rutting Index 76°C, penetration, and softening point 31.7, and 54.70°C, respectively	Hu et al. (2021)
Hydrochar for electricity generation	2	The average calorific value of hydrochar was 32% higher than waste materials; HTC provided 70% hydrochar yield and 84% energy efficiency	Hantoro et al. (2020)
Hydrochar for supercapacitor electrode materials	3	Microwave-assisted HTC was used to synthesize supercapacitor electrode materials from corn straw with potassium catalyst (30 wt%)	Liu et al. (2020)
HTC used to convert exhausted *Chlorella vulgaris* into hydrochar	2	Combining hydrochar production with algal biodiesel process, found to be feasible for solid fuel production and waste disposal	Lee et al. (2018)

[a]*Note: TRL, Technology Readiness Level.*

of different hydrochar applications to achieve a circular economy and contribute towards achieving SDGs.

As shown in **Table 2**, despite the numerous applications of hydrochar, the available information on its use to reduce adverse environmental impacts of cities or generate sustainable construction practices using local materials is very limited.

For example, selected studies on converting sewage sludge and municipal solid waste to hydrochar are included in **Table 2**, where the use of different additives was tested to increase the heating value of produced hydrochar or machine learning tools were explored to predict hydrochar properties. However, no information is available for scale-up operation of hydrochar production and its evaluation under field conditions. The production of hydrochar from either municipal solid waste or sewage sludge is a topic receiving significant attention in recent years (Sharma and Dubey, 2020; Huezo et al., 2021; Liu et al., 2021). However, it is worth noting that the technology readiness level is very low for all cases. This is a significant knowledge gap as there is a need for technologies that incorporate circular economy principles to establish sustainable communities. The lack of information on further technology demonstration, system development and launch and operation may delay implementation or even hinder knowledge of their technologic and economic feasibility, which in turn could result in failure of the timely achievement of SDGs goals.

Using hydrochar from solid waste for the improvement of asphalt surfaces for road construction has attracted attention recently because the application of solid wastes to road infrastructure through its conversion to hydrochar provides a practical and economical solution to the construction and maintenance of roads, especially in rural areas with a ready supply of feedstocks available for large-scale hydrochar synthesis. Augmented rheological properties of hydrochar-modified asphalt have been reported, which has also been suggested as an environmentally friendly asphalt modifier (Qin et al., 2021). Other studies, however, have suggested that hydrochar has adverse impacts on road surfaces as it increases bitumen viscosity, thus creating difficulties with workability and poor storage stability (Wu and Hu, 2021). These conflicting findings present an interesting avenue for further research. Assessing whether hydrochar performance as an asphalt modifier depends on its chemical and/or physical characteristics is fundamental to better understanding its potential use. Finding engineering solutions to overcome drawbacks on the use of hydrochar from solid waste as an asphalt modifier can open the door for circular economy solutions for sustainable solid waste management.

The application of hydrochar for energy-related applications such as electricity generation or energy storage is also gaining traction. For example, the use of hydrochar made of kitchen waste has been reported with a high potential for energy storage (Zhou et al., 2021). Researchers have found that hydrochar, as a supercapacitor, surpassed the performance of commercial activated carbon, reaching specific energy values 6.66 and 8.52 Wh/kg in acidic and neutral electrolytes, respectively (Lang et al., 2021). The effect of HTC variables on the performance of the hydrochar produced, though, remains poorly understood and has been identified as an important knowledge gap that merits further exploration to optimize the process and produce the best materials for energy storage.

Similarly, generating hydrochar from spent algal materials after biofuel extraction is another promising application of circular economy. For example, using such hydrochar (5 wt%) has been reported to have more than double co-hydrothermal gasification yield (Sztancs et al., 2020). Several challenges, however, remain to be answered, including problems associated with processing aqueous phase discharges with a diluted load of by-products (e.g., microalgal slurry) (Khoo et al., 2020). The impact of the solid content of spent algal waste on hydrochar production yield is a significant knowledge gap worthy of further exploration. Addressing the problem of using dilute microalgal slurry (e.g., 1 wt% biomass) for hydrothermal treatment will allow recovery of valuable materials in addition to biofuels production from biorefinery processes.

CONCLUSION

As evident from the above discussion, hydrochar production and application is a promising pathway towards a circular economy and achieving UN SDGs through water treatment and waste management. However, significant research gaps exist and will need to be addressed as a matter of priority due to the SDGs timeframe. It is important to note that the current research tends to focus on the application of hydrochar for treating non-potable water such as stormwater and wastewater output from other treatment technologies (e.g., industrial treatment plants, bioretention systems and wetlands) (Cui et al., 2020; Merzari et al., 2020; Wang et al., 2021). Therefore, critical research gaps exist in the area of utilizing hydrochar for large-scale drinking water treatment to address SDG-6 directly. Similarly, although several laboratory-scale studies (**Table 2**) have shown the promise of converting different waste biomass to valuable hydrochar based products, such technologies are in their infancy and need further development and optimization of parameters to enable making a significant contribution to improve human wellbeing and contribute to achieving the UN SDGs. Therefore, although promising in principle, hydrochar research needs the immediate attention of the research community, industry, and policymakers to make a lasting and positive impact on the environment in the current SDG cycle and beyond.

AUTHOR CONTRIBUTIONS

LP—Conceptualisation, Literature Review, Coordination, Writing the Original Draft, Revising. EB—Conceptualisation, Literature Review, Writing the Original Draft, Revising. BW—Literature Review, Writing the Original Draft AG—Conceptualisation, Coordination, Review. NB—Review and Proofread.

REFERENCES

Banerjee, A., Banerjee, A. V., and Duflo, E. (2011). *Poor Economics: A Radical Rethinking of the Way to Fight Global Poverty: Public Affairs*. New York: PublicAffairs.

Benstoem, F., Becker, G., Firk, J., Kaless, M., Wuest, D., Pinnekamp, J., et al. (2018). Elimination of Micropollutants by Activated Carbon Produced from Fibers Taken from Wastewater Screenings Using Hydrothermal Carbonization. *J. Environ. Manage.* 211, 278–286. doi:10.1016/j.jenvman.2018.01.065

Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., et al. (2021). Multifunctional Applications of Biochar beyond Carbon Storage. *Int. Mater. Rev.*, 1–51. doi:10.1080/09506608.2021.1922047

Çatlıoğlu, F., Akay, S., Gözmen, B., Turunc, E., Anastopoulos, I., Kayan, B., et al. (2020). Fe-modified Hydrochar from orange Peel as Adsorbent of Food Colorant Brilliant Black: Process Optimization and Kinetic Studies. *Int. J. Environ. Sci. Tech.* 17 (4), 1975–1990. doi:10.1007/s13762-019-02593-z

Cheng, F., Porter, M. D., and Colosi, L. M. (2020). Is Hydrothermal Treatment Coupled with Carbon Capture and Storage an Energy-Producing Negative Emissions Technology? *Energ. Convers. Manage.* 203, 112252. doi:10.1016/j.econman.2019.11225210.1016/j.enconman.2019.112252

Cui, X., Lu, M., Khan, M. B., Lai, C., Yang, X., He, Z., et al. (2020). Hydrothermal Carbonization of Different Wetland Biomass Wastes: Phosphorus Reclamation and Hydrochar Production. *Waste Manage.* 102, 106–113. doi:10.1016/j.wasman.2019.10.034

Delgado-Moreno, L., Bazhari, S., Gasco, G., Méndez, A., El Azzouzi, M., and Romero, E. (2021). New Insights into the Efficient Removal of Emerging Contaminants by Biochars and Hydrochars Derived from Olive Oil Wastes. *Sci. Total Environ.* 752, 141838. doi:10.1016/j.scitotenv.2020.141838

Fang, J., Gao, B., Chen, J., and Zimmerman, A. R. (2015). Hydrochars Derived from Plant Biomass under Various Conditions: Characterization and Potential Applications and Impacts. *Chem. Eng. J.* 267, 253–259. doi:10.1016/j.cej.2015.01.026

Gallucci, K., Taglieri, L., Papa, A. A., Di Lauro, F., Ahmad, Z., and Gallifuoco, A. (2020). Non-Energy Valorization of Residual Biomasses *via* HTC: CO2 Capture onto Activated Hydrochars. *Appl. Sci.* doi:10.3390/app10051879

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., and Hultink, E. J. (2017). The Circular Economy - A New Sustainability Paradigm? *J. Clean. Prod.* 143, 757–768. doi:10.1016/j.jclepro.2016.12.048

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A Review on Circular Economy: the Expected Transition to a Balanced Interplay of Environmental and Economic Systems. *J. Clean. Prod.* 114, 11–32. doi:10.1016/j.jclepro.2015.09.007

Hantoro, R., Septyaningrum, E., Siswanto, B. B., and Izdiharrudin, M. F. (2020). Hydrochar Production through the HTC Process: Case Study of Municipal Solid Waste Samples in East Java, Indonesia. *Solid Fuel Chem.* 54, 418–426. doi:10.3103/s036152192006004x

Hoang, S. A., Bolan, N., Madhubashani, A. M. P., Vithanage, M., Perera, V., Wijesekara, H., et al. (2022). Treatment Processes to Eliminate Potential Environmental Hazards and Restore Agronomic Value of Sewage Sludge: A Review. *Environ. Pollut.* 293, 118564. doi:10.1016/j.envpol.2021.118564

Hu, C., Feng, J., Zhou, N., Zhu, J., and Zhang, S. (2021). Hydrochar from Corn Stalk Used as Bio-Asphalt Modifier: High-Temperature Performance Improvement. *Environ. Res.* 193, 110157. doi:10.1016/j.envres.2020.110157

Huang, Y., Zhao, Y.-j., Hao, Y.-h., Wei, G.-q., Feng, J., Li, W.-y., et al. (2019). A Feasibility Analysis of Distributed Power Plants from Agricultural Residues Resources Gasification in Rural China. *Biomass and Bioenergy* 121, 1–12. doi:10.1016/j.biombioe.2018.12.007

Huezo, L., Vasco-Correa, J., and Shah, A. (2021). Hydrothermal Carbonization of Anaerobically Digested Sewage Sludge for Hydrochar Production. *Bioresour. Tech. Rep.* 15, 100795. doi:10.1016/j.biteb.2021.100795

Jackson, T. (2009). *Prosperity without Growth: Economics for a Finite Planet.* London: Routledge.

Jasemizad, T., Sun, P., and Padhye, L. P. (2021). Aqueous N-Nitrosamines: Precursors, Occurrence, Oxidation Processes, and Role of Inorganic Ions. *Crit. Rev. Environ. Sci. Tech.*, 1–47. doi:10.1080/10643389.2021.1930439

Khoo, C. G., Lam, M. K., Mohamed, A. R., and Lee, K. T. (2020). Hydrochar Production from High-Ash Low-Lipid Microalgal Biomass *via* Hydrothermal Carbonization: Effects of Operational Parameters and Products Characterization. *Environ. Res.* 188, 109828. doi:10.1016/j.envres.2020.109828

Kumar, R., Sarmah, A. K., and Padhye, L. P. (2019a). Fate of Pharmaceuticals and Personal Care Products in a Wastewater Treatment Plant with Parallel

Secondary Wastewater Treatment Train. *J. Environ. Manage.* 233, 649–659. doi:10.1016/j.jenvman.2018.12.062

Kumar, R., Tscharke, B., O'Brien, J., Mueller, J. F., Wilkins, C., and Padhye, L. P. (2019b). Assessment of Drugs of Abuse in a Wastewater Treatment Plant with Parallel Secondary Wastewater Treatment Train. *Sci. Total Environ.* 658, 947–957. doi:10.1016/j.scitotenv.2018.12.167

Kumar, S., Loganathan, V. A., Gupta, R. B., and Barnett, M. O. (2011). An Assessment of U(VI) Removal from Groundwater Using Biochar Produced from Hydrothermal Carbonization. *J. Environ. Manage.* 92 (10), 2504–2512. doi:10.1016/j.jenvman.2011.05.013

Lang, J., Matějová, L., Cuentas-Gallegos, A. K., Lobato-Peralta, D. R., Ainassaari, K., Gómez, M. M., et al. (2021). Evaluation and Selection of Biochars and Hydrochars Derived from Agricultural Wastes for the Use as Adsorbent and Energy Storage Materials. *J. Environ. Chem. Eng.* 9, 105979. doi:10.1016/j.jece.2021.105979

Lee, J., Lee, K., Sohn, D., Kim, Y. M., and Park, K. Y. (2018). Hydrothermal Carbonization of Lipid Extracted Algae for Hydrochar Production and Feasibility of Using Hydrochar as a Solid Fuel. *Energy* 153, 913–920. doi:10.1016/j.energy.2018.04.112

Lenka, S. P., Kah, M., and Padhye, L. P. (2022). Occurrence and Fate of Poly- and Perfluoroalkyl Substances (PFAS) in Urban Waters of New Zealand. *J. Hazard. Mater.* 428, 128257. doi:10.1016/j.jhazmat.2022.128257

Li, J., Zhu, X., Li, Y., Tong, Y. W., Ok, Y. S., and Wang, X. (2021). Multi-task Prediction and Optimization of Hydrochar Properties from High-Moisture Municipal Solid Waste: Application of Machine Learning on Waste-To-Resource. *J. Clean. Prod.* 278, 123928. doi:10.1016/j.jclepro.2020.123928

Liu, D., Wang, Y., Jia, B., Wei, J., Liu, C., Zhu, J., et al. (2020). Microwave-Assisted Hydrothermal Preparation of Corn Straw Hydrochar as Supercapacitor Electrode Materials. *ACS Omega* 5, 26084–26093. doi:10.1021/acsomega.0c03605

Liu, T., Li, Y., Peng, N., Lang, Q., Xia, Y., Gai, C., et al. (2017). Heteroatoms Doped Porous Carbon Derived from Hydrothermally Treated Sewage Sludge: Structural Characterization and Environmental Application. *J. Environ. Manage.* 197, 151–158. doi:10.1016/j.jenvman.2017.03.082

Liu, Y., Sun, Y., Wan, Z., Jing, F., Li, Z., Chen, J., et al. (2021). Tailored Design of Food Waste Hydrochar for Efficient Adsorption and Catalytic Degradation of Refractory Organic Contaminant. *J. Clean. Prod.* 310, 127482. doi:10.1016/j.jclepro.2021.127482

Liu, Z., and Zhang, F. S. (2009). Removal of lead from Water Using Biochars Prepared from Hydrothermal Liquefaction of Biomass. *J. Hazard. Mater.* 167 (1), 933–939. doi:10.1016/j.jhazmat.2009.01.085

Lv, B.-W., Xu, H., Guo, J.-Z., Bai, L.-Q., and Li, B. (2022). Efficient Adsorption of Methylene Blue on Carboxylate-Rich Hydrochar Prepared by One-step Hydrothermal Carbonization of Bamboo and Acrylic Acid with Ammonium Persulphate. *J. Hazard. Mater.* 421, 126741. doi:10.1016/j.jhazmat.2021.126741

Magdziarz, A., Mlonka-Mędrala, A., Sieradzka, M., Aragon-Briceño, C., Pożarlik, A., Bramer, E. A., et al. (2021). Multiphase Analysis of Hydrochars Obtained by Anaerobic Digestion of Municipal Solid Waste Organic Fraction. *Renew. Energ.* 175, 108–118. doi:10.1016/j.renene.2021.05.018

Mau, V., and Gross, A. (2018). Energy Conversion and Gas Emissions from Production and Combustion of Poultry-Litter-Derived Hydrochar and Biochar. *Appl. Energ.* 213, 510–519. doi:10.1016/j.apenergy.2017.11.033

Merrey, D. (2015). *The Critical Role of Water in Achieving the Sustainable Development Goals: Synthesis of Knowledge and Recommendations for Effective Framing, Monitoring, and Capacity Development. Draft Report*. New York, USA: United Nations Department of Economic and Social Affairs. Retrieved 30/01/2022, from.

Merzari, F., Goldfarb, J., Andreottola, G., Mimmo, T., Volpe, M., and Fiori, L. (2020). Hydrothermal Carbonization as a Strategy for Sewage Sludge Management: Influence of Process Withdrawal point on Hydrochar Properties. *Energies* 13 (11), 2890. doi:10.3390/en13112890

Mittapalli, S., Sharma, H. B., and Dubey, B. K. (2021). Hydrothermal Carbonization of Anaerobic Granular Sludge and Co-pelletization of Hydrochar with Yard Waste. *Bioresour. Tech. Rep.* 14, 100691. doi:10.1016/j.biteb.2021.100691

Nadarajah, K., Bandala, E. R., Zhang, Z., Mundree, S., and Goonetilleke, A. (2021). Removal of Heavy Metals from Water Using Engineered Hydrochar: Kinetics and Mechanistic Approach. *J. Water Process Eng.* 40, 101929. doi:10.1016/j.jwpe.2021.101929

Parshetti, G. K., Chowdhury, S., and Balasubramanian, R. (2014). Hydrothermal Conversion of Urban Food Waste to Chars for Removal of Textile Dyes from Contaminated Waters. *Bioresour. Tech.* 161, 310–319. doi:10.1016/j.biortech.2014.03.087

Peng, X., Yan, Z., Cheng, X., Li, Y., Wang, A., and Chen, L. (2019). Quaternary Ammonium-Functionalized rice Straw Hydrochar as Efficient Adsorbents for Methyl orange Removal from Aqueous Solution. *Clean. Techn Environ. Pol.* 21 (6), 1269–1279. doi:10.1007/s10098-019-01703-2

Qin, W., Hu, C., and Meng, Y. (2021). Research on Rheological Property of Hydrochar Based Bio Modified Asphalt Binder: A Promising Way to Solve Environmental Problems Caused by Waste Corn Stalks. *Construction Building Mater.* 308, 125005. doi:10.1016/j.conbuildmat.2021.125005

Regmi, P., Garcia Moscoso, J. L., Kumar, S., Cao, X., Mao, J., and Schafran, G. (2012). Removal of Copper and Cadmium from Aqueous Solution Using Switchgrass Biochar Produced *via* Hydrothermal Carbonization Process. *J. Environ. Manage.* 109, 61–69. doi:10.1016/j.jenvman.2012.04.047

Ritchie, H., and Roser, M. (2021). *Clean Water and Sanitation*. Published online at OurWorldInData org. Retrieved on 25/1/2022 from. Available at: https://ourworldindata.org/.

Roman, F. F., Diaz de Tuesta, J. L., Praça, P., Silva, A. M. T., Faria, J. L., and Gomes, H. T. (2021). Hydrochars from Compost Derived from Municipal Solid Waste: Production Process Optimization and Catalytic Applications. *J. Environ. Chem. Eng.* 9, 104888. doi:10.1016/j.jece.2020.104888

Sachs, J. D. (2015). *The Age of Sustainable Development*. Columbia University Press.

Sharma, H. B., and Dubey, B. K. (2020). Binderless Fuel Pellets from Hydrothermal Carbonization of Municipal Yard Waste: Effect of Severity Factor on the Hydrochar Pellets Properties. *J. Clean. Prod.* 277, 124295. doi:10.1016/j.jclepro.2020.124295

Shettigondahalli Ekanthalu, V., Narra, S., Sprafke, J., and Nelles, M. (2021). Influence of Acids and Alkali as Additives on Hydrothermally Treating Sewage Sludge: Effect on Phosphorus Recovery, Yield, and Energy Value of Hydrochar. *Processes* 9, 618. doi:10.3390/pr9040618

Sumarajand Padhye, L. P. (2017). Influence of Surface Chemistry of Carbon Materials on Their Interactions with Inorganic Nitrogen Contaminants in Soil and Water. *Chemosphere* 184, 532–547. doi:10.1016/j.chemosphere.2017.06.021

SumarajXiong, Z., Sarmah, A. K., and Padhye, L. P. (2020). Acidic Surface Functional Groups Control Chemisorption of Ammonium onto Carbon Materials in Aqueous media. *Sci. Total Environ.* 698, 134193. doi:10.1016/j.scitotenv.2019.134193

Sztancs, G., Juhasz, L., Nagy, B. J., Nemeth, A., Selim, A., Andre, A., et al. (2020). Co-Hydrothermal Gasification of Chlorella Vulgaris and Hydrochar: The Effects of Waste-To-Solid Biofuel Production and Blending Concentration on Biogas Generation. *Bioresour. Tech.* 302, 122793. doi:10.1016/j.biortech.2020.122793

Tasca, A. L., Puccini, M., Gori, R., Corsi, I., Galletti, A. M. R., and Vitolo, S. (2019). Hydrothermal Carbonization of Sewage Sludge: A Critical Analysis of Process Severity, Hydrochar Properties and Environmental Implications. *Waste Manage.* 93, 1–13. doi:10.1016/j.wasman.2019.05.027

Teng, F., Zhang, Y., Wang, D., Shen, M., and Hu, D. (2020). Iron-modified rice Husk Hydrochar and its Immobilization Effect for Pb and Sb in Contaminated Soil. *J. Hazard. Mater.* 398, 122977. doi:10.1016/j.jhazmat.2020.122977

Tripathi, M., Sahu, J. N., and Ganesan, P. (2016). Effect of Process Parameters on Production of Biochar from Biomass Waste through Pyrolysis: A Review. *Renew. Sustain. Energ. Rev.* 55, 467–481. doi:10.1016/j.rser.2015.10.122

UN_Water (2020). *UN Water SDG Data Portal*. The United NationsRetrieved 10/07/2020from. Available at: https://www.sdg6data.org/.

UNDESA (2020). *SDG Indicators. Statistics Devision, Department of Economic and Social Affairs (DESA) of the United Nations*. Retrieved 10/07/2020, from.

UNDESA (2018). *The Sustainable Development Goals Report 2018*. New York, USA: United Nations Department of Economic and Social Affairs.

UNGA (2019). *Draft Concept and Programme for the Joint Meet Ing of the Economic and Financial (Second Committee) of the 73rd UN General Assembly and the UN Economic and Social Council.*

Van Hullebusch, E. D., Bani, A., Carvalho, M., Cetecioglu, Z., De Gusseme, B., Di Lonardo, S., et al. (2021). Nature-Based Units as Building Blocks for Resource Recovery Systems in Cities. *Water* 13, 3153. doi:10.3390/w13223153

Wang, F., Wang, H., Sun, C., and Yan, Z. (2021). Conventional Bioretention Column with Fe-Hydrochar for Stormwater Treatment: Nitrogen Removal, Nitrogen Behaviour and Microbial Community Analysis. *Bioresour. Tech.* 334, 125252. doi:10.1016/j.biortech.2021.125252

Wilk, M., Śliz, M., and Lubieniecki, B. (2021). Hydrothermal Co-carbonization of Sewage Sludge and Fuel Additives: Combustion Performance of Hydrochar. *Renew. Energ.* 178, 1046–1056. doi:10.1016/j.renene.2021.06.101

Wu, X., and Hu, C. (2021). Greener Solution to Waste Corn Stalks and Shortage of Asphalt Resource: Hydrochar Produced by Hydrothermal Carbonization as a Novel Performance Enhancer for Asphalt Binder. *Materials* 14, 1427. doi:10.3390/ma14061427

Zhang, X., Gao, B., Fang, J., Zou, W., Dong, L., Cao, C., et al. (2019). Chemically Activated Hydrochar as an Effective Adsorbent for Volatile Organic Compounds (VOCs). *Chemosphere* 218, 680–686. doi:10.1016/j.chemosphere.2018.11.144

Zhang, Y.-N., Guo, J.-Z., Wu, C., Huan, W.-W., Chen, L., and Li, B. (2022). Enhanced Removal of Cr(VI) by Cation Functionalized Bamboo Hydrochar. *Bioresour. Tech.* 347, 126703. doi:10.1016/j.biortech.2022.126703

Zhou, Y., Shi, W., Engler, N., and Nelles, M. (2021). High-value Utilization of Kitchen Waste Derived Hydrochar in Energy Storage Regulated by Circulating Process Water. *Energ. Convers. Manage.* 229, 113737. doi:10.1016/j.enconman.2020.113737

Zhu, X., Liu, Y., Qian, F., Zhou, C., Zhang, S., and Chen, J. (2014). Preparation of Magnetic Porous Carbon from Waste Hydrochar by Simultaneous Activation and Magnetization for Tetracycline Removal. *Bioresour. Tech.* 154, 209–214. doi:10.1016/j.biortech.2013.12.019

Zhu, X., Liu, Y., Qian, F., Zhou, C., Zhang, S., and Chen, J. (2015). Role of Hydrochar Properties on the Porosity of Hydrochar-Based Porous Carbon for Their Sustainable Application. *ACS Sustain. Chem. Eng.* 3 (5), 833–840. doi:10.1021/acssuschemeng.5b00153

Zvimba, J. N., Musvoto, E. V., Nhamo, L., Mabhaudhi, T., Nyambiya, I., Chapungu, L., et al. (2021). Energy Pathway for Transitioning to a Circular Economy within Wastewater Services. *Case Stud. Chem. Environ. Eng.* 4, 100144. doi:10.1016/j.cscee.2021.100144

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.