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REVIEW ARTICLE

Sustainable resource recovery and process improvement in anaerobic digesters using hydrochar: A circular bio-economic perspective

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Abstract

Hydrothermal carbonization (HTC) is a promising technology for waste valorisation and nutrient recovery to achieve sustainability. HTC converts organic waste into hydrochar, a carbon-rich solid with numerous surface functionalities that can be used for energy and wastewater treatment. In this review, we highlight the potential of hydrochar-based technology for improving the performance of anaerobic digestion (AD) systems and downstream applications of nutrient-laden hydrochar. We identify knowledge gaps in hydrochar production, performance in AD systems and nutrient recovery, including the need for larger-scale production facilities, multielement adsorption studies, and computational modelling. Techno-economic analysis and life cycle assessment of hydrochar applications are critical to evaluating the commercial viability of this technology. Overall, hydrochar-based technology offers a sustainable solution for waste management and resource recovery, with potential socioeconomic benefits for developing economies. The deployment of hydrochar-based technology will directly address key issues highlighted in the United Nations' Sustainable Development Goals such as Clean water and sanitation (SDG 6); Zero hunger (SDG 2); and Climate action (SDG 13) thereby contributing to a more sustainable future.

KEYWORDS
anaerobic digestion, hydrochar, hydrothermal carbonization, nutrient recovery, soil amelioration

1 | BACKGROUND

Water quality degradation is a pressing issue that results from rapid urbanisation, indiscriminate discharge of industrial effluents and poor governance. Climate change and extreme seasonal variations further exacerbate the problem of water scarcity. About 80% of the wastewater released into the environment is untreated municipal wastewater, with regional variations (>99% in Africa, 65% in Asia, 34% in Europe and 10% in the United States) (UnitedNations, 2016). The release of wastewater containing nutrients such as nitrogen (N) and phosphorus (P) beyond the permissible limits of 10 mg L^{-1} of total N and 0.05 mg L^{-1} of *P* leads to eutrophication and deterioration of aquatic ecosystems (IPCC, 2014). Approximately 16.6 million metric tons of N and 3 million metric tons of P are discharged annually via wastewater (380 billion cubic metres in 2020), and their complete recovery can reduce the global nutrient demand for agriculture by 13.4% (UNU-INWEH, 2020). The planetary boundary framework estimates that the anthropogenic release of nitrogen (150 Tg N yr^{-1}) and phosphorus (22 Tg P yr^{-1}) into the environment have crossed beyond the "zone of uncertainty" (62 Tg N yr^{-1} and 11 Tg P yr^{-1}), indicating a high-risk category (Steffen et al., 2015). Besides wastewater, the carbon-rich wastes from agriculture systems are a crucial problem due to the lack of sustainable management practises (e.g., incineration, open dumping and/or landfilling). For example, cereal crop straw contributes significantly to agricultural waste, with an estimated 973.9 Mt (Atinkut et al., 2020). Addressing this problem requires innovative biomass valorisation technologies that limit threats to both ecosystem and human health.

Anaerobic digestion (AD) is a widely used wastewater treatment process that converts complex organic fractions into biogas rich in methane, which can be used as an energy source. The average methane recovery rate from an AD plant in the United Kingdom is approximately 15.9 kg CH_4 hr^{-1} (Bakkaloglu et al., 2021). However, the poor efficiency of the AD plants due to operational instabilities caused by multiple factors remains a key concern. AD plants also harbour high levels of nutrients (N & P) in various forms that can be recovered (Wu et al., 2021). While conventional filters can remove nutrients in suspended or precipitated forms from wastewater, the removal of dissolved forms is challenging and requires energy-intensive and expensive equipment (Wu et al., 2021). There is an immediate need to shift from conventional wastewater treatment to a resource recovery approach that utilises appropriate desorption technologies to generate revenue and upgrade the nutrient economy from a linear path to a circular bioeconomy. The recovered nutrients in various forms could be recycled via streamlined applications to soil and other related agricultural practices.

In the case of nutrient recovery, adsorption-based technologies play an integral role offering low-cost materials generated using waste-derived carbon-based materials (Manyuchi et al., 2018). These carbon materials produced using thermochemical biomass conversion technologies have been successfully trialled for adsorptive removal of nutrients (Oumabady et al., 2021; Spataru et al., 2016; Wu et al., 2021). Specifically, a new-age carbon material such as "hydrochar" is gaining momentum in the field of waste management and wastewater treatment, and the environmental applications of hydrochar has been reviewed in detail by Masoumi et al. (2021). Hydrochar is different from biochar based on the type of waste used and the method of production. Wet waste upon subjecting to hydrothermal carbonization under pressurized condition produces hydrochar while dry waste upon pyrolysis produces biochar (Leithaeuser et al., 2022). Owing to the series of reactions that take place during the HTC process, the resultant carbon material acquires favourable properties for multidisciplinary environmental applications (Azzaz et al., 2020).

Here, we highlight significant knowledge gaps on hydrochar production, application in anaerobic digesters and potential use for nutrient recovery from waste streams. Specifically, we offer our perspective on the role of hydrochar in circular economy strategies that would create a sustainable value-addition pipeline to the hydrochar-based recovery of nutrients and its downstream applications.

1.1 | Hydrochar

Hydrothermal carbonization (HTC) is a thermo-chemical biomass conversion technology with potential applications in various energy and green chemistry domains (Masoumi et al., 2021). The process involves carbonising wet waste between 180°C and 250°C, under auto-generated pressure conditions (18–20 bars), to produce a condensed carbon product known as "hydrochar." Hydrochar can be produced from a wide range of carbon-rich wastes, including agricultural biomass, sewage sludge, algae and food and animal wastes. During hydrochar production, a variety of reactions occur (such as depolymerization, decarboxylation, dehydration, demethylation, and repolymerization), resulting in specific properties that make it suitable for environmental applications such as soil amendment, carbon sequestration, pollutant and contaminant adsorption, catalyst support, energy alternative, and electrochemical supercapacitors (Masoumi et al., 2021).

Our previous research has highlighted different environmental applications of hydrochar produced from paper board mill sludge. We have demonstrated that hydrochar can serve as a viable energy alternative option by blending it with coal at equal proportions, delivering a higher heating value (HHV) of 22.25 MJ kg^{-1} compared to commercial coal's 15–25 MJ kg^{-1} (Oumabady et al., 2020). We also found that hydrochar can be effective in removing orthophosphates and diclofenac from aqueous solutions, with adsorption capacities of 9.59 and 37.23 mg g^{-1}, respectively (Oumabady et al., 2021, 2022). In wastewater treatment, hydrochar has shown unique adsorbent properties due to the formation of deprotonated functional groups on its surface, such as phenolic and carboxylic groups, which make it a highly effective adsorbent compared to other wet waste-derived adsorbent materials (Delahaye et al., 2020).

The composition of hydrochar is determined by various parameters including feedstock characteristics, temperature, residence time, biomass to water ratio, and pH (Leng et al., 2020). Moreover, the composition is subjective to both qualitative and quantitative variations (e.g., the carbon content and yield), which determines its application.

Feedstock composition is a critical factor that determines the hydrochar's carbon content and yield. Co-HTC of non-lignocellulosic biomass with lignocellulosic biomass has been shown to improve the adsorbent property, energy yield, coalification degree, and fixed carbon content of hydrochar (Song et al., 2019). This approach could enable the blending of waste from various sources and offer an effective solution for large-scale hydrochar production. In addition to feedstock composition, temperature is a critical factor that determines the structural morphology and elemental composition of the hydrochar and influences chemical reactions during the carbonization process (Nakason et al., 2018). Scalable manufacturing units have been established to produce hydrochar commercially in a semi-continuous process. Major commercial operators of hydrochar production plants include Ingelia Avalon, Antaco, Suncoal, TerraNova, AVA Biochem and C-Green Technology AB (Fernández-Sanromán et al., 2021).

1.2 | Hydrochar in AD systems and nutrient recovery

Hydrochar supplementation in ADs can increase methane yield potential by 20%–30% and help nutrient recovery by excluding their toxic effects in their reactive forms such as ammonia, that can inhibit the activity of methanogenic archaea (Wu et al., 2021). The impact of hydrochar in anaerobic digesters and methane recovery is summarized in Table 1 and Figure 1. Hydrochar acts as an electron bridge that facilitates direct interspecies electron transfer (DIET) between hydrochar and microorganisms in the AD, promoting better biogas production by improving the association between hydrochar and microorganisms (Xu et al., 2018). Hydrochar produced at lower temperatures (<200°C) can harbour high pore density and cavities facilitating more microbial interactions (Zhou et al., 2020). Moreover, the redox chemistry of hydrochar can also impact CH_4 production with sludge-based hydrochar generating more CH_4 due to its abundant oxygen-containing surface functionalities (Ren et al., 2020).

While the impact of hydrochar on biogas production from AD is well established, there is still a lack of mechanistic understanding of microorganisms-hydrochar interactions at both single-cell and community levels. Critical knowledge gaps include,

(i) a mechanistic understanding of hydrochar-driven DIET,
(ii) the impact on different functional guilds of methanogenic archaea (i.e., methylotrophic, acetogenic and hydrogenotrophic methanogens),

TABLE 1 Summary of data from studies on the impact of hydrochar on methane generation in anaerobic digestion systems.

Hydrochar feedstock	Hydrochar concentration (g L^{-1})	Increase in CH_4 yield (%)	Reference
Rice straw	2–10	60.7 and 90.8	Xu et al. (2018)
Bamboo	1:2[a]	127	Choe et al. (2019)
Corn straw	10	84	Usman et al. (2020)
Dewatered sewage sludge	1–20	5.6–44.5	Ren et al. (2020)
Microalgae chlorella	2.6–6.5	31	Wang et al. (2020)
Macroalgae	1:1[a]	38	
Sewage sludge + municipal solid waste	1–25	14.8–44.5	Pagés-Díaz and Huiliñir (2020)
Sewage sludge	4	27 and 49	Xu et al. (2020)
	4	49	
Swine manure	4	17	
Sewage digestate	15	64.7	Ahmed et al. (2021)
Corn straw	10	23.7–57.8	He et al. (2021)
Tofu residue	4	18–19	Choe et al. (2021)
Poplar	10	13.7–228.5	Usman et al. (2021)
Dewatered sludge	5	14.0	Leithaeuser et al. (2022)
Corn straw	10	50	Shi et al. (2021)
	10	24	
Coffee grounds	10	29	Li et al. (2022)
Oak husk	5	17	Murillo et al. (2022)
Organic digestate	10	26.99	Xu et al. (2022)

[a]Hydrochar to substrate ratio.

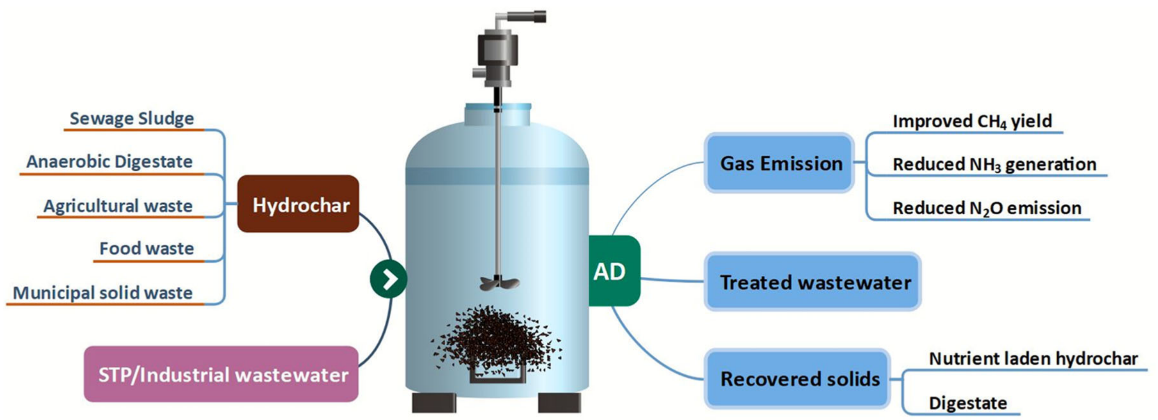

FIGURE 1 Schematic figure representing the use of hydrochar and its benefits in anaerobic digestion (AD) systems.

(iii) microbial surface colonisation on hydrochar and
(iv) impact on the flow of essential nutrients such as N, P, and C at the community level.

To address these gaps, we suggest a multiscale approach that is, single-cell approaches (e.g., Raman Spectroscopy, scanning electron microscopy [SEM]) to understand surface colonisation, and community-level interactions using eco-physiological tools, such as stable-isotope probing (SIP) (Kumaresan et al., 2011) and BioOrthogonal Noncanonical Amino Acid Tagging (BONCAT) (Hatzenpichler et al., 2014).

The effectiveness of hydrochar in resource recovery depends on the type of functionalization and its resultant surface chemical properties. The adsorption mechanism is based on complexation, hydrogen bonding, electrostatic interaction, ion exchange, pore filling, physical adsorption, and π–π interactions. Chemical surface modifications can enrich oxygenated functional groups, promoting target-specific adsorption. However, surface modifications will need to be tailored for specific nutrients to be recovered. Although functionalized composites have a minor influence at the nanoscale interface and lack local homogeneity for the materials, surface grafting and doping of the hydrochar matrix can overcome these barriers with balanced acid-base and redox chemistry (Khan et al., 2019). Further research on the development of customized hydrochar can help recover specific nutrients from wastewater-treating ADs.

1.3 | Potential benefits in nutrient recovery by hydrochar

The addition of hydrochar produced at temperatures below 200°C to anaerobic digesters can offer multiple benefits. First, due to its oxygen-rich surface functionalities (such as hydroxylic, carboxylic, and ketonic groups), it can adsorb various cationic molecules specifically NH_4 and H_2S, thereby excluding their toxic effects and promoting methanogenesis (Xu et al., 2018). Furthermore, when applied to soil, hydrochar can supply NH_4 to plant growth by desorption thereby serving as a sustainable nitrogen source. Second, hydrochar can also facilitate phosphate recovery from wastewater due to the presence of iron and aluminium oxides in its skeleton (Oumabady et al., 2021). The use of kinetic and isothermal models can help determine the maximum nutrient adsorption capacities of hydrochar for different applications. Additionally, hydrochar containing iron oxides can increase its adsorption potential towards specific compounds, and iron oxide-impregnated hydrochar ensures a higher recovery rate due to its magnetic properties (Patiño et al., 2021). One promising approach is to pack hydrochar into filter sachets, which can supplement the AD process and facilitate nutrient recovery. This nutrient-rich hydrochar can then be recycled and used as soil amendment.

2 | NUTRIENT-RICH HYDROCHAR APPLICATION IN SOIL

2.1 | Slow-release fertiliser

The nutrient composition of hydrochar depends on the feedstock and/or the carbonisation conditions. Hydrochar is rich in primary plant nutrients such (N, P and K) and in secondary nutrients (Ca and Mg), yet it varies based on the feedstock and HTC conditions (Khosravi et al., 2022). Organic manure-derived hydrochar are rich in essential plant nutrients and supplies N directly to the plant due to the electrostatic upholding of inorganic N (NH_4^+ and NO_3^-) originating from the biomass (Yu et al., 2019). The presence of hydrochar at lower concentrations in soil has been shown to promote the availabilities of P, K and Ca to several plants and thus improving productivity (Fornes & Belda, 2018). This demonstrates the potential use of hydrochar as a P fertilizer rather than as a N fertilizer, since P in hydrochar is mostly present in Al and Ca-associated forms which would dissociate and ensure the availability over a longer period (Shi et al., 2019). Hydrochar produced at lower temperatures (<200°C) release P at a faster rate while the hydrochar produced at higher temperatures (>200°C) release *N* at a faster rate (Wu et al., 2021). Additionally, the abundant oxygen functional groups (COO– and CO–) on its surface increase the cation exchange capacity of the soil and enable ammonium ion adsorption, thereby retaining N in the soil. Functionalisation of hydrochar for specific nutrients can improve nutrient recovery from AD systems, and the nutrient-rich hydrochar can be used as a slow-release fertilizer. However, it is important to be tailored to specific soil properties and crops (Figure 2). Hydrochar application to the soil initially inhibited seed germination at a concentration above 30% due to the production of several phyto-toxic substances (glycolic acid, levulinic acid and guaiacol) during HTC. Detoxification of hydrochar before application could be a suitable alternative that includes drying/wetting of hydrochar, washing with hot/cold water, composting/co-composting, and aging through storage. This would result in the reducing the effects of phytotoxicity and promotes plant growth through gradual supply of nutrients (Dalias et al., 2018).

2.2 | Substitute for peat

Peat is commonly used as an organic supplement to improve soil properties, but recently, hydrochar is receiving greater attention as a substitute for peat media (Álvarez et al., 2017). Research has shown that the addition of hydrochar to the peat can enhance air space, water retention and enzymatic activity without affecting the microbial community (Dalias et al., 2018). There is still scope for optimizing hydrothermal conditions to produce hydrochar with similar hydro-physical properties to peat, which can subsequently lead to its utilisation in growth media and soil cover. Since peat is a nonrenewable resource, replacing it with hydrochar can offer a sustainable solution. Hydrochar applications have been proved to improve the physical properties of soil in terms of porosity, bulk density, respiration, water holding capacity and available water capacity (Khosravi et al., 2022). Initial application of hydrochar as a substitute to peat showed negative effects on germination index due to the presence of phytotoxic compounds, however, upon washing followed by thermal treatment, a positive correlation has been observed (Suarez et al., 2023). In addition, the presence of hydrochar promotes the root growth by three times at 5% concentration in peat due to the combined effect of aforementioned factors (Farru et al., 2022).

2.3 | Carbon sequestration

The effectiveness of hydrochar as an amendment in the soil to facilitate carbon sequestration is still being debated, particularly concerning the stability of hydrochar in soils (Gronwald et al., 2016). However, studies have shown that hydrochar-amended soil contains more aromatic compounds than carbohydrates due to its influence on microbial communities that metabolize labile fractions of soil organic carbon (Sun et al., 2020). Hydrochar produced at higher temperatures are more stable and recalcitrant than the counterpart produced at

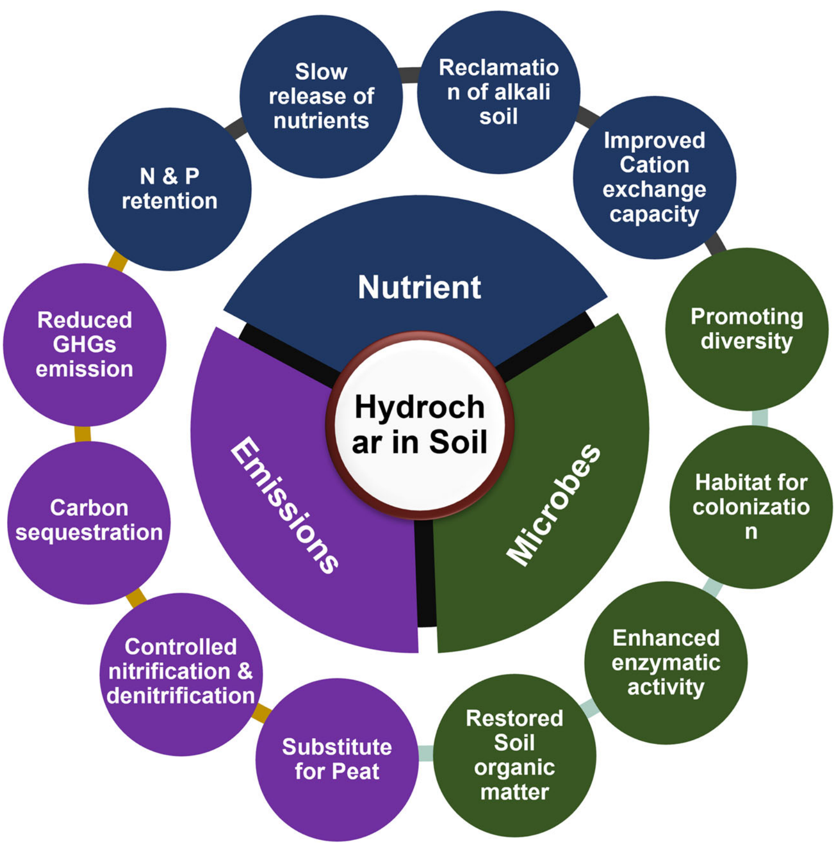

FIGURE 2 Downstream application of hydrochar as soil amendment and the potential benefits.

lower temperatures. Upon application to the soil, it stabilizes the soil organic carbon (SOC) pool thereby reducing the related emissions specifically in sandy soils (de Jager et al., 2022). This would form the basis for the carbon sequestration potential of hydrochar and ensures specific application requirements. Although hydrochar shows higher initial rate of decomposition in soil (around 30%), the rest two-thirds (around 60%) remained stable over a long period with an estimated half-life of 19 years. Due to this stability and the potential to restore native soil organic carbon, hydrochar could provide a decadal solution for carbon sequestration (Malghani et al., 2015). Therefore, the benefits of hydrochar should be explored for long-term sequestration studies under different soil conditions.

2.4 | Soil microorganisms

The potential synergistic interactions of hydrochar with soil microorganisms, particularly members within the domain Bacteria and Archaea, have been studied by researchers, with cascading influences on nutrient cycling (Islam et al., 2021). Hydrochar can offer a perfect localised habitat for microbial colonisation and prevent their dormancy, owing to its higher surface area, well-developed pores and other physicochemical properties (Ren et al., 2020). The pore size depends on the type of feedstock and HTC conditions. The acidic nature of the hydrochar has been reported to promote the growth of fungal communities, specifically the spore germination of arbuscular mycorrhizal fungi which could be exploited cumulatively to reclamate alkali soil conditions (Sun et al., 2020). Hydrochar addition can influence soil enzymatic activity, particularly reducing soil urease activity while increasing the abundance of nitrifiers (based on the abundance of the gene *amoA* encoding for the enzyme ammonia monooxygenase) when it was microbially aged, which eventually reduces the NH_4^+–N concentrations. The impact of hydrochar amendment in the soil to decrease NH_3 volatilization in rice paddy fields can reduce the loss of nitrogen from the soil (Yu et al., 2020). On the contrary, hydrochar application in soil has also been shown to enhance nitrogen immobilization with reduced activity of both nitrification and denitrification processess (Wang et al., 2015). Due to the presence of dissolved organic carbon (DOC), the labile form of carbon serves as a easily accessible carbon source for the microbial communities (Thunshirn et al., 2021). It has been shown that hydrochar addition can promote the activity of microbial communities involved DOC decomposition (*Flavobacterium, Anaerolinea, Penicillium, and Acremonium*) while negatively impacting the activity of the microorganisms involved in polycyclic aromatic hydrocarbon (PAH) degradation (*Sphingobacterium*) (Sun et al., 2020). Phytotoxic compounds produced during the HTC process can also pose a potential threat to the soil fauna, specifically impacting the ecology of earthworms and associated microorganisms (Khosravi et al., 2022). Moisture-rich feedstock used in the HTC process can result in the coproduction of bio-oil alongside hydrochar. The bio-oil produced with hydrochar is rich in fatty acids and minerals with potential agricultural and industrial applications (Azzaz et al., 2020). Various research on the impact of hydrochar on soil microorganism activity and diversity highlights contrary findings and given the heterogenous nature of the soil matrix across different scales, alongside the nature of hydrochar, we suggest field trials should be focussed to a particular agro-ecosystem and crops. Specifically, the use of recent development in molecular ecology and Omic tools can offer better insights into the impact of hydrochar on microbial diversity and function.

2.5 | Mitigation of climate-active gas emissions

The use of hydrochar as a soil amendment to mitigate greenhouse gases (GHGs) from agricultural soil and grasslands is gaining momentum. However, conflicting observations have been reported, particularly about the stability of hydrochar in different soil (Gronwald et al., 2016). Hydrochar produced at temperatures under 200°C has been shown to increase GHG emissions due to its high labile carbon content compared to that produced at higher temperatures, which contains more aromatic carbon and enhanced CH_4-producting microbial communities (Khosravi et al., 2022). Hydrochar modified with amino silane has been shown to reduce carbon dioxide emissions from soil (Vieillard et al., 2018). Soil application of hydrochar has also been shown to reduce CO_2 emissions by 34% and increase crop yield with effective nutrient management compared to urea application (Adjuik et al., 2020). Moreover, hydrochar offers an effective solution for crop residue management after harvest, restores soil organic carbon, and improves water-holding capacity. Reduction in nitrous oxide (N_2O) emissions has also been documented in hydrochar-applied soils, possibly due to electrostatic interaction and sorption of NH_3 and NH_4^+ by hydrochar. However, the influence of hydrochar characteristics on soil N_2O emissions and N cycling is often contradictory and may depend on soil type and microbial functional diversity (Wang et al., 2015). Research in this area is currently limited to laboratory-scale microcosms that may not accurately represent the in situ impact on soil ecosystems. To maximize the potential of hydrochar in mitigating soil GHG emissions, future research should focus on field-level studies that include a comprehensive analysis of the impact of hydrochar on physical, chemical and biological characteristics of soil.

2.6 | Knowledge gaps in hydrochar production and application

Hydrochar, despite having a rich variety of surface functionalities, remains an underexploited resource. One of the key challenges is the lack of large-scale production facilities to process waste. Proof of principle work is mostly performed using batch-type hydrothermal autoclave reactors, and wider use of the bench-scale hydrochar-driven system for nutrient recovery should be developed, tested and optimised before field-scale implementations. Moreover, the fabrication of continuous/batch reactors with higher capacity is critical to address fundamental knowledge gaps in hydrochar production and nutrient recovery in AD systems. Further research is required to understand the multielement adsorption process in hydrochar, specifically focusing on intermolecular competition (nutrients, metals, PPCPs and emerging contaminants) for the active sites and customising the hydrochar surface for specific molecular interaction. By employing the kinetics and isothermal models, the maximum adsorption capacities, equilibrium time and order of adsorption can be derived for a comprehensive recovery. In the case of application in AD systems, computational modelling can be used to link microbiome data with physiochemical parameters to optimize the adsorption parameters for nutrient removal using hydrochar. This can enable the design of a prefabricated hydrochar-based microbial biofilter system that can be used for nutrient recovery from wastewater streams. Additionally, the development of predictive algorithms based on machine learning, tailored for specific characteristics of hydrochar, will facilitate quick optimisation of the desired qualities in hydrochar-driven systems.

2.7 | Techno-economics of HTC strategies

A comprehensive evaluation of the techno-economic analysis and life cycle assessment of hydrochar applications in AD systems and downstream applications of nutrient-laded hydrochar recovered from AD systems are needed, which should be tailored to specific waste streams (Sangaré et al., 2022). The initial capital cost, cost of operation, feedstock value and other related costs should be assessed and compared to the income generated through the downstream application of hydrochar. While the energy content of hydrochar could offset input costs, further value addition should be integrated to generate additional revenue benefits, making the production commercially viable. Moreover, the life cycle assessment of hydrochar should be in line with the local regulatory limits.

Although commercial-scale production units are just starting to gain momentum, feasibility studies should analyse waste generation and its management through this technology at both local and continental scales. Effective commercialisation can offer socioeconomic benefits via employment benefits in the Global South. Techno-economic analysis should also involve experts, such as environmental microbiologists, engineers, geochemists, soil and social scientists, to perform a comprehensive analysis of the field-scale implementation of HTC technology, mass-energy balances, downstream applications and assess its long-term economic performance. The PEST Analysis, commonly used tool for analysing Political, Economic, Socio-Cultural, and Technological developments can be used to obtain an in-depth knowledge of the hydrochar-driven economy.

3 | CONCLUSIONS

In conclusion, hydrochar-based technology offers a sustainable solution for waste management strategies, particularly for improving the operation efficiency of AD systems and resource recovery. HTC is notable for its ease of adaptability and does not require expensive instruments. Field-scale implementations of this technology have the potential to bring a paradigm shift in the hydrochar-based circular bioeconomy and improve environmental resilience through effective resource recovery (nitrogen/phosphorus) and improved energy production from ADs. The utilization of agro-waste in hydrochar production promotes the profitable reuse of organic residues and will contribute to achieving zero-emissions goals. Deploying hydrochar-based technology improves the performance of ADs and also recover nutrients for downstream application in soil amelioration. This will address key issues highlighted in 10 (of 17) UN's sustainable development goals (SDGs), both directly and indirectly, and benefit a large number of stakeholders in developing economies, particularly the low- and middle-income countries. Overall, we synthesise the requirements for further research to understand and optimize the production and application of hydrochar to maximize its potential in the circular bioeconomy. Techno-economic analyses and life cycle assessments will be crucial to evaluate the commercial feasibility and environmental impact of this technology. By addressing these knowledge gaps and challenges, hydrochar-based technology can contribute significantly to sustainable waste management, environmental resilience and achieving the SDGs.

AUTHOR CONTRIBUTIONS

Sadish Oumabady: Conceptualization; writing—original draft; visualization; funding acquisition. **Sangeetha P. Ramasamy**: Writing—original draft. **S. Paul Sebastian**: Writing—review and editing. **Rajinikanth Rajagopal**: Writing—review and editing. **Parthiba K. Obulisamy**: Writing—review and editing. **Rory Doherty**: Writing—review and editing. **Sree Nanukuttan**: Writing—review and editing. **Satish K. Bhardwaj**: Conceptualization; writing—review and editing; supervision. **Deepak Kumaresan**: Conceptualization; writing—original draft; supervision; project administration.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable—no new data generated.

ETHICS STATEMENT

Not applicable.

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