# Paving the way for biochar production, supply chain, and applications toward a sustainable future

Siyuan Zhou [a], Xiaohan Yang [a], Thien-Khanh Tran [b], Jian Shen [c], Chunjiang An [a,*]

[a] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal H3G 1M8, Canada
[b] Scientific Research and International Affairs Department, Gia Dinh University, Ho Chi Minh City 700000, Viet Nam
[c] Department of Process Engineering, Memorial University of Newfoundland, St. John's A1C 5S7, Canada

ABSTRACT

Biochar, which results from biomass pyrolysis in the absence of oxygen, has been considered a beneficial substance that can enhance environmental benefits. This paper discusses its manufacturing, issues, and uses while focusing on the circular economy aspect. In the past, biochar was used to enhance soil fertility and water treatment; nowadays, it is used for the supply of energy, cleaning up pollutants, and construction materials. The use of new feedstocks like algae and invasive plant species enhances its production and applications. In addition, with the help of digital technology, the biochar supply chain has been improved, thus making it productive and efficient. Biochar emerges as a key factor and beneficiary of green technology advancements that have catalyzed applications in batteries and supercapacitors within energy storage systems. Furthermore, biochar can play a role in the sequestration and reuse of greenhouse gases as well as the reduction of pollution to the environment. Lastly, this research provides an overview of how biochar production and usage, in the face of global environmental challenges and dilemmas, should be enhanced and developed to support sustainable industrialization.

## 1. Introduction

Biochar is a carbon-rich material produced through pyrolysis, a process that heats organic waste materials in the absence of oxygen (Khater et al., 2024). Significant interest has been attributed to its effectiveness in improving soil properties, carbon storage, and bioremediation. From an ecological perspective, biochar satisfies the principles of a circular economy system as it recycles waste while creating utility simultaneously (Yaashikaa et al., 2020). Its production also helps minimize waste products, facilitate using recycled materials, and lower environmental effects like greenhouse gas emissions.

There have been a wide range of applications of biochar on land restoration and water treatment. (Wang et al., 2022; Zhang et al., 2023). However, improved knowledge has expanded its applicability to sophisticated uses in contemporary technology-related areas. The introduction of new feedstocks and the application of digital technology in biochar production are strategic improvements (Wang et al., 2024). In addition, biochar is considered a material for energy storage devices such as batteries and supercapacitors due to its porosity and conductivity (Senthil and Lee, 2021; Sun et al., 2024). Another use is attributed to its efficiency in the extraction of contaminants such as microplastics

and heavy metals from water and soil, making it useful for environmental use (Miranda Zoppas et al., 2023). These new directions on biochar reflect its growing role in sustainable agriculture and innovative environmental technologies.

The focus of this paper is to examine new possibilities for biochar production involving innovative feedstocks, digital supply chains, and novel applications in energy and the environment. The research specifically focuses on: (i) renewable and unconventional biomass sources for sustainable biochar production, (ii) digital technologies for enhancing supply chain efficiency, and (iii) biochar's role in pollutant removal, greenhouse gas mitigation, and advanced energy storage systems. By achieving these objectives, the study demonstrates how biochar can become a key catalyst for circular economy innovation and green technologies.

## 2. Emerging feedstocks and innovative materials in biochar production

New trends in biochar development include more innovative, effective, and less-explored feedstocks for biochar generation. In addition to conventional agricultural waste and nut shells, there are new

opportunities within the framework of feedstock. While many studies have been conducted regarding the sludge generated from wastewater treatment plants, new forms of sludge such as biorefinery sludge as well as from advanced wastewater treatment processes may hold new opportunities (Romero-Güiza et al., 2022). These sludge types contain high organic content and have higher adsorption capacity after being transformed into biochar (Zhou et al., 2024). This makes them highly effective in capturing heavy metals and organic contaminants, aiding in environmental cleanup efforts. With the increased implementation of biorefineries, sludge from these sources becomes another stream for generating biochar, which adds value to waste management while enhancing resource recovery (Waqas et al., 2023).

Algae are emerging as a promising renewable and rapidly growing feedstock. Biochar derived from algae has a large surface area that has been found to be highly effective in environmental cleanup (Amalina et al., 2022). Experimental research demonstrates that algae-derived biochar has high adsorption capacities for heavy metals and nutrients, which indicates its potential applicability for environmental management particularly in areas impacted by industrial effluents or agricultural leaching (Dong et al., 2023). A major strength is that algae can grow very fast and in various conditions, making it very suitable for scaling up biochar production. Recent pilot projects have shown that it is feasible to convert algae that grow in large quantities in eutrophic lakes into biochar (Sheng et al., 2022). Such projects with water bodies not only assist in the primary management of algae overgrowth but also produce biochar as a byproduct, offering opportunities for both algae management and sustainable biochar production (Vasseghian et al., 2024). This two-fold strategy highlights the increasing viability of algae and other new biomass sources in biochar generation. Current studies have also pointed out that algae can be used in capturing carbon, as the algae themselves can initially uptake large amounts of $CO_2$ before being converted to biochar. This process not only promotes carbon emission reduction but also sustainable biochar production, making it an ideal approach for both environmental cleanup and climate change mitigation (Yang et al., 2024).

Some invasive plant species such as water hyacinth and kudzu can also be used as feedstock for the production of biochar. These species are usually seen as having negative impacts on ecosystems; however, they can be collected and turned into biochar – thus, turning a source of concern into an opportunity. Water hyacinth, for instance, has tremendous prospects in biochar production because of its high biomass productivity and its ability to remove pollutants from water bodies (Lewoyehu et al., 2024). This technique not only helps to mitigate the hazards posed by invasive plants but also produces useful biochar for environmental applications.

However, one of the drawbacks of algae and other wet biomass feedstocks is the high moisture content, which, if not well managed, can lead to high energy consumption during pyrolysis. To overcome this limitation, drying, dewatering, or torrefaction before the actual pre-treatment process has been suggested. These methods minimize the amount of moisture left in the biochar, allowing for better energy efficiency and overall improving the quality of biochar. Additionally, incorporating waste heat recovery systems or even solar drying systems would enhance the energy efficiency of processing wet biomass in a cost-effective manner.

Due to the small size of the localized materials such as algae and invasive plants, a decentralized model of biochar production is feasible. This makes it possible for biochar facilities to be established strategically near biomass sources because transport costs affect the efficiency of the biochar production process (Saharudin et al., 2024). Additionally, studies prove that biochar from these feedstocks can be as effective, or even more, than conventional feedstocks, making them suitable for full-scale use. While new feedstocks and technological options are being introduced, their macro-environmental consequences for large-scale use also need to be thoroughly examined in the future.

## 3. Optimizing supply chain through digital technologies

Biochar production depends on an efficient logistic chain because biomass feedstocks, which include agricultural residues and organic waste, are widely distributed. These feedstocks are sometimes deposited in remote areas, making their collection, transport, and storage significant concerns. These challenges include high cost of transportation, congestion in the supply chain, fluctuating biomass supply throughout the year, and contamination issues during sorting. The solutions to these challenges involve applying new technologies for managing operations, emissions, and costs.

One research finding that may offer a solution is the use of Supply Chain Digital Twins (SCDTs), which mimic the physical supply chain in real-time. In the case of SCDTs, biochar producers can monitor biomass stock, transportation, and facility production capabilities to implement real-time modifications to boost efficiency (Wang et al., 2022). In this way, feedstock data allows biochar producers to make real-time adjustments, leading to optimization, elimination of constraints, and increased production efficiency (Astarita et al., 2024). For example, SCDT models can estimate biomass availability and plan transport logistics. The application of SCDT technology has proven effective in improving the logistics of biochar production by reducing both cost and emissions thus highlighting the value of this technology in sustainable biomass management (Fig. 1).

Fig. 1 shows how new technologies integrate into the supply chain of biochar to improve efficiency and sustainability. It begins with biomass feedstock, with a special emphasis on collection, transportation, and production. Some of these technologies include better use of artificial intelligence in sorting of waste, digital twins for modelling of supply chain, and using robotics in production. They allow regular updates, which improve efficiency, reduce emissions, and increase the quality of biochar. The integrated process emphasizes socioeconomic returns and environmental stewardship to capture the promise of biochar for enhancing resource productivity.

In addition to digital twins, artificial intelligence technologies are among the revolutionary tools in the production of biochar. Intelligent sorting methods are employed in treatment plants to sort feedstocks according to their nature within waste dumps (Ukoba and Jen, 2022). They reduce the involvement of human operators, improve the sorting methods, and provide clean feedstock that is required in the production of good-quality biochar (Olawade et al., 2024). By applying the machine learning approach, the nature of feedstocks is identified, which makes material selection precise and reduces fluctuations in manufacturing.

Automated technologies for biochar production have been successfully implemented in several pilot projects to optimize the process in biochar production facilities. For example, the production process can be simulated using a digital twin, starting from biomass collection to the production of biochar, allowing plant managers to make adjustments based on real-time data (Spinti et al., 2022). In situations where biomass supply is seasonal or by location-dependent, digital twins help facilities find more efficient ways to transport biomass or change production rates for the shortest time possible (Khanal et al., 2023). Thus, large-scale waste treatment facilities have reported increased sorting accuracy through the use of AI-based systems (Mulè, 2024). These systems measure biomass in real-time, ensuring that only the most suitable feedstocks are used for biochar production (Balakrishnan et al., 2024). This automation reduces production costs, increases production rates, and lowers contamination levels, resulting in higher-quality biochar.

Over time, the integration of AI and big data appears to create a chance of having biochar production plants fully automated (Nguyen et al., 2024). These technologies can assist the plants in setting the production rates, transportation schedules, and resource usage by assessing market needs and managing biomass supply, all without human intervention (Arias et al., 2023). This could lead to lower costs associated with biochar production and increased process efficiency, making it possible to scale up operations to support major
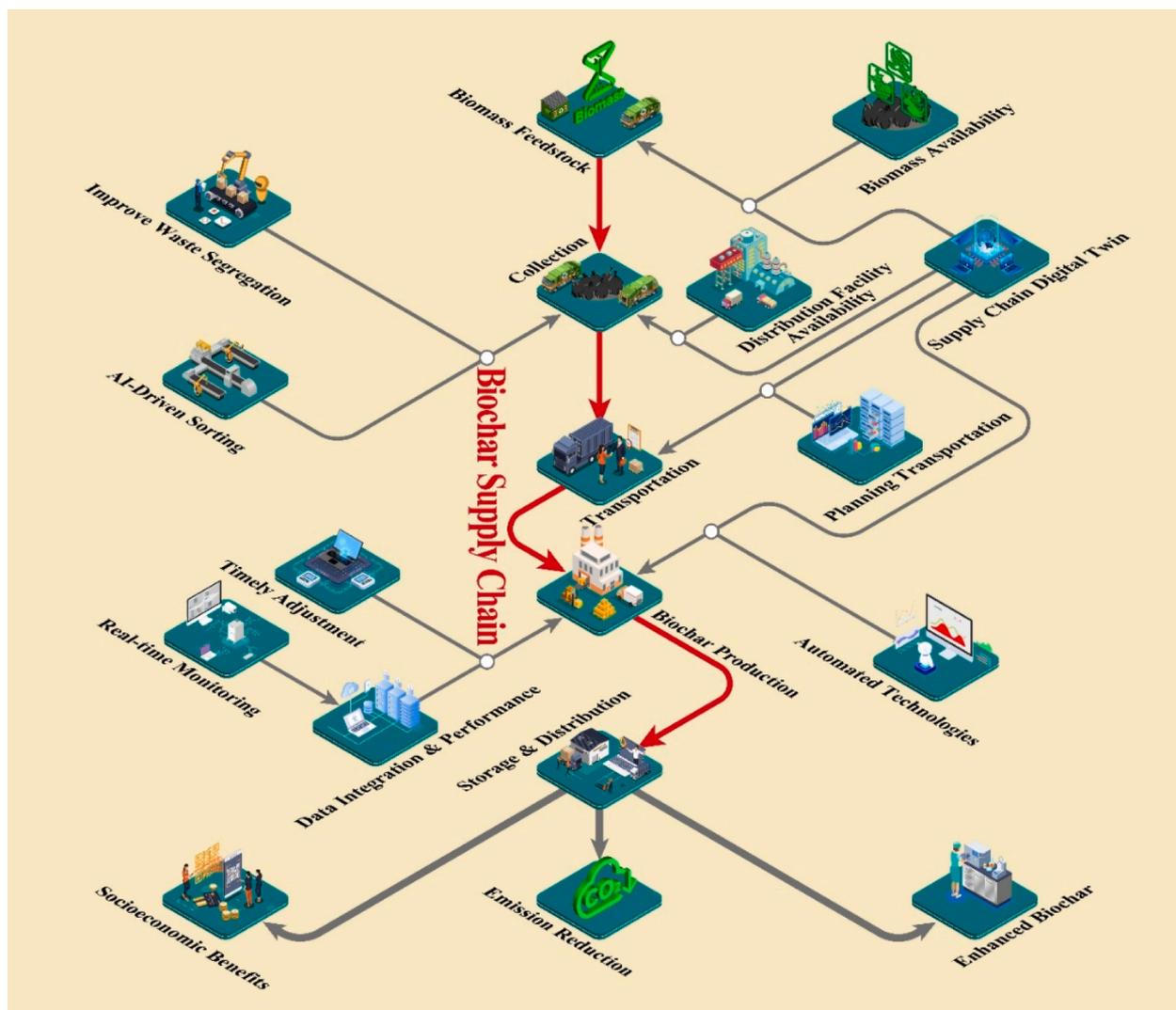
**Fig. 1.** Biochar supply chain with digital twin technology integrated for monitoring and optimization.

environmental rehabilitation efforts and resource conservation.

## 4. Biochar as a sustainable solution in advanced energy storage and beyond

Recent developments have positioned biochar as a viable material for energy storage technologies, with its potential applications in lithium-ion and sodium-ion batteries. Carbonaceous materials traditionally used as electrodes in these batteries can be expensive and present sustainability challenges. Biochar derived from renewable and sustainable resources has advantages over conventional chemical and physical methods because of its large surface area and electrical conductivity (Soltani et al., 2021). These characteristics enable biochar to effectively store and release energy, making it suitable for widespread use in battery electrodes (Fig. 2). Some researchers have demonstrated that biochar-based electrodes can be produced at a lower cost than standard materials, while also sequestering carbon during the synthesis process (Qin et al., 2020).

In addition to batteries, supercapacitors are another application in which biochar shows great potential. High charge density and energy retention offered by biochar provide advantages for supercapacitors that are specifically developed for rapid energy storage and release at much higher rates (Khedulkar et al., 2024). Biochar has been shown to enhance the capacity and potentially extend the longevity of

supercapacitor devices when incorporated into their electrodes. This research aims to contribute to a growing field of interest in energy storage systems that require increased efficiency, sustainability, and low cost.

Bamboo biochar, derived from bamboo, is one of the fastest-growing and renewable biomass sources in the world and has been discussed in the literature for energy storage applications (Wang et al., 2024). These studies also show that bamboo biochar can provide greater energy densities than traditional carbon-based electrode materials used in batteries and supercapacitors. Nonetheless, the discussion of bamboo biochar needs to go beyond energy densities to consider important features such as thermal stability, lifecycle performance and compatibility with improved electrode designs. Its porous structure, surface functionality, and structural transformability to accommodate multiple energy storage configurations have also been explored in existing studies, uncovering opportunities to further enhance its performance.

Furthermore, comparisons with biochar from other biomass types, such as rice husks and coconut shells, reveal the benefits of using bamboo biochar and potential improvements in its preparation and use. For example, bamboo biochar's structural characteristics and bio-based origin make it an ideal option for future carbon energy storage materials. By addressing these multifaceted aspects, bamboo biochar study can provide a roadmap for its utilization in other intricate energy systems and contribute to the development of secure, sustainable, and
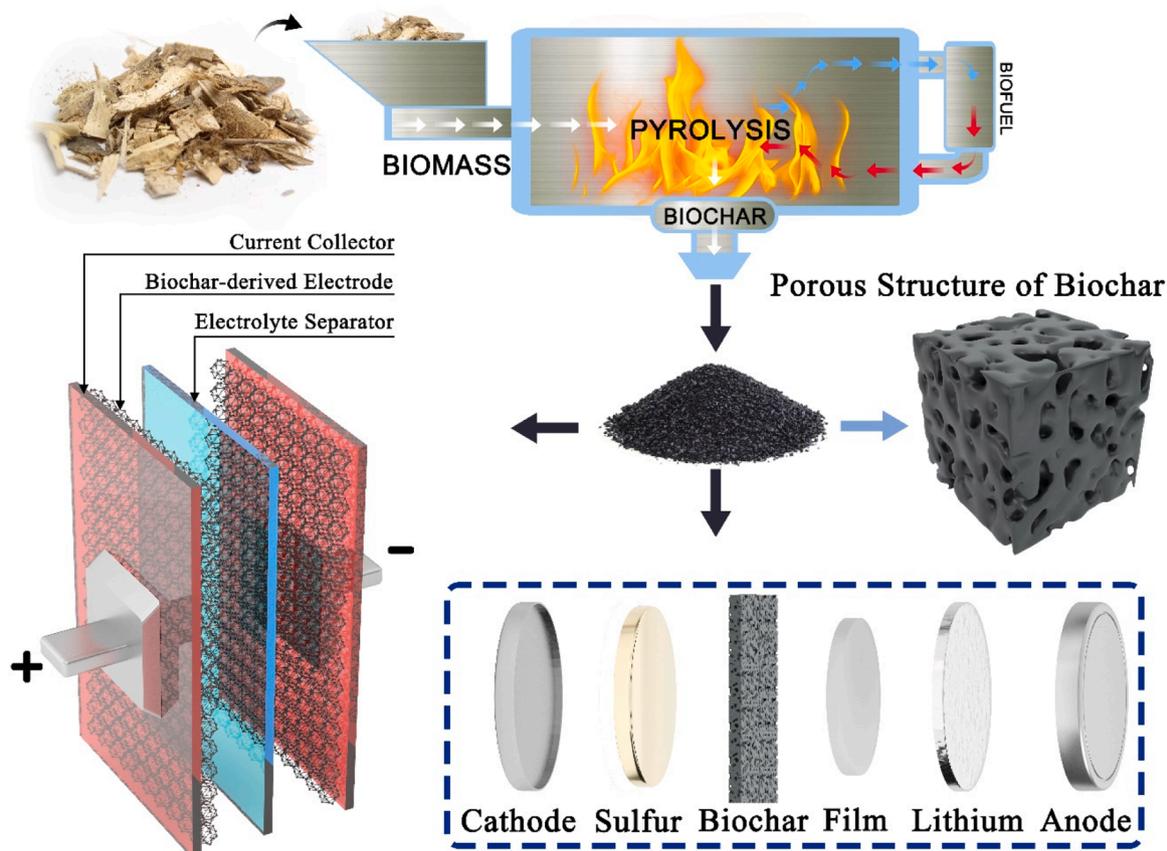
**Fig. 2.** Schematic illustration of biochar derived from biomass for applications in supercapacitors and batteries.

environment-friendly technologies.

## 5. Using biochar to address emerging environmental problems and support the circular economy

Biochar is a sustainable byproduct of biomass pyrolysis and has been used in various environmental remediations (Das, 2024; Shen et al., 2018). It is now also being applied to address some emerging environmental problems. Biochar has been found to have the ability to physically capture the microplastics in water due to its structure together with high porosity and adsorption capacity (Cao et al., 2024). As plastics build up in the environment, biochar filtration has the potential to play a key role in water treatment, benefiting both developing nations and developed urban wastewater systems that experience high levels of microplastics.

Recent studies have aimed to enhance the use of biochar for microplastic removal by incorporating advanced materials such as graphene oxide (Abuwatfa et al., 2021). Research from the last two years shows that these biochar-graphene composites significantly improve adsorption capacity, particularly for filtering microplastics from high-throughput water systems (Abuwatfa et al., 2021). Although still in its developmental stage, this kind of technology shows great potential for scaling up, thus making biochar a viable solution to one of the most persistent pollution problems.

Biochar has demonstrated potential in reducing greenhouse gas emissions, especially methane in agriculture. Methane, one of the most potent greenhouse gases, is primarily emitted from livestock and agricultural management activities (Chen et al., 2020; Ngo et al., 2024). Incorporating biochar into manure management enhances its ability to adsorb methane and other gases due to its porous structure, preventing these gases from being released into the atmosphere (Li et al., 2022). In addition, there is always the challenge of resolving the contaminated

land problem (Wei et al., 2011). The use of biochar also improves soil management by sequestering heavy metals like lead and cadmium, limiting their potential to contaminate water sources (He et al., 2019). In its modified form, particularly when combined with nanomaterials, biochar has an even higher adsorption rate, physically binding to contaminants and immobilizing them in the soil. This not only improves soil quality but also reduces environmental pollution from dangerous substances. Furthermore, biochar is used in environmental sensors that monitor pollutants in the atmosphere and water systems, serving as new tools for the monitoring and management of environmental problems. In the context of a circular economy, biochar is being applied to construction composites to create lightweight, high-strength structures. These reinforced composites possess characteristics of biochar, such as thermal insulation and carbon storage, making them suitable for sustainable construction (Barbhuiya et al., 2024).

The usage of biochar is also expected to grow in response to stricter pollution regulations, as biochar is effective in pollution control. As an environmental material, its ability to filter microplastics, trap methane, and capture heavy metals makes it a valuable resource, especially for industrialized nations seeking to adopt sustainable practices (Samuel Olugbenga et al., 2024).

Potential future applications include water purification, land restoration, and air filtration. Future studies may focus on enhancing biochar's effectiveness by incorporating other materials such as graphene and nanotechnology, which could expand the range of contaminants it can adsorb (Nosratabad et al., 2024). Furthermore, biochar could play an important role in carbon management strategies aimed at addressing climate change (Afshar and Mofatteh, 2024). With advances in technology and increased governmental support, biochar has the potential to provide sustained environmental benefits and address pressing sustainability challenges. It should be noted that the economic evaluation challenges may stem from the high cost of production, the inability to

achieve significant economies of scale, and the limited availability of feedstock (Yaashikaa et al., 2020). Additionally, unpredictable rules and regulations persist, and the market has yet to offer solutions for widespread applications. Addressing these issues, along with those related to the benefits of applying biochar, ensures that the concept's wide-ranging prospects for environmental sustainability are thoroughly considered.

## 6. Conclusions

Biochar is useful in many ways beyond climate change mitigation, focusing on its potential in environmental management, innovation, and advancing circular economy approaches. Socially, it can be used in sustainable agriculture and clean energy so as to help communities achieve better living standards and promote global sustainable development aspirations. In the environmental context, it has benefits such as sequestration, pollutant abatement, and reducing greenhouse gas emissions which are useful in combating climate change. The study suggests a notably urgent need for existing and emerging feedstocks in biochar production, continued investments in digital technologies, and innovative supply chain management. However, challenges such as high production costs, production scale limitations, and various legislative constraints should be considered. Further research should focus on addressing production costs, expanding the use of renewable energy sources, and developing adequate legislation. With further advancements and greater integration of different sectors in the use of technology, biochar has the potential to become a key solution for driving positive change in the environment and reducing social inequalities.

## CRediT authorship contribution statement

**Yang Xiaohan:** Investigation. **Zhou Siyuan:** Writing – original draft, Visualization, Investigation, Conceptualization. **Shen Jian:** Writing – review & editing. **Tran Thien-Khanh:** Writing – review & editing. **An Chunjiang:** Writing – review & editing, Supervision, Resources.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

## Data availability

No data was used for the research described in the article.

## References

Abuwatfa, W.H., Al-Muqbel, D., Al-Othman, A., Halalsheh, N., Tawalbeh, M., 2021. Insights into the removal of microplastics from water using biochar in the era of COVID-19: a mini review. Case Stud. Chem. Environ. Eng. 4, 100151. https://doi.org/10.1016/j.cscee.2021.100151.

Afshar, M., Mofatteh, S., 2024. Biochar for a sustainable future: environmentally friendly production and diverse applications. Results Eng., 102433 https://doi.org/10.1016/j.rineng.2024.102433.

Amalina, F., Razak, A.S.A., Krishnan, S., Sulaiman, H., Zularisam, A.W., Nasrullah, M., 2022. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – a review. J. Hazard. Mater. Adv. 7, 100134. https://doi.org/10.1016/j.hazadv.2022.100134.

Arias, A., Feijoo, G., Moreira, M.T., 2023. How could Artificial Intelligence be used to increase the potential of biorefineries in the near future? a review. Environ. Technol. Innov. 32, 103277. https://doi.org/10.1016/j.eti.2023.103277.

Astarita, V., Guido, G., Haghshenas, S.S., Haghshenas, S.S., 2024. Risk reduction in transportation systems: the role of digital twins according to a bibliometric-based literature review. Sustainability 16 (8), 3212. https://doi.org/10.3390/su16083212.

Balakrishnan, D., Sharma, P., Bora, B.J., Dizge, N., 2024. Harnessing biomass energy: advancements through machine learning and AI applications for sustainability and efficiency. Process Saf. Environ. Prot. https://doi.org/10.1016/j.psep.2024.08.084.

Barbhuiya, S., Bhusan Das, B., Kanavaris, F., 2024. Biochar-concrete: a comprehensive review of properties, production and sustainability. Case Stud. Constr. Mater. 20, e02859. https://doi.org/10.1016/j.cscm.2024.e02859.

Cao, N.D.T., Vo, D.H.T., Pham, M.D.T., Nguyen, V.T., Nguyen, T.B., Le, L.T., Mukhtar, H., Nguyen, H.V., Visvanathan, C., Bui, X.T., 2024. Microplastics contamination in water supply system and treatment processes. Sci. Total Environ. 926, 171793. https://doi.org/10.1016/j.scitotenv.2024.171793.

Chen, Z., An, C., Fang, H., Zhang, Y., Zhou, Z., Zhao, Y., Zhao, S., 2020. Assessment of regional greenhouse gas emission from beef cattle production: a case study of Saskatchewan in Canada. J. Environ. Manag. 264, 110443. https://doi.org/10.1016/j.jenvman.2020.110443.

Das, S.K., 2024. Adsorption and desorption capacity of different metals influenced by biomass derived biochar. Environ. Syst. Res. 13 (1), 5. https://doi.org/10.1186/s40068-024-00335-w.

Dong, M., He, L., Jiang, M., Zhu, Y., Wang, J., Gustave, W., Wang, S., Deng, Y., Zhang, X., Wang, Z., 2023. Biochar for the removal of emerging pollutants from aquatic systems: a review. Int. J. Environ. Res. Public Health 20 (3), 1679. https://doi.org/10.3390/ijerph20031679.

He, L., Zhong, H., Liu, G., Dai, Z., Brookes, P.C., Xu, J., 2019. Remediation of heavy metal contaminated soils by biochar: mechanisms, potential risks and applications in China. Environ. Pollut. 252, 846–855. https://doi.org/10.1016/j.envpol.2019.05.151.

Khanal, S.K., Tarafdar, A., You, S., 2023. Artificial intelligence and machine learning for smart bioprocesses. Bioresour. Technol. 375, 128826. https://doi.org/10.1016/j.biortech.2023.128826.

Khater, E.S., Bahnasawy, A., Hamouda, R., Sabahy, A., Abbas, W., Morsy, O.M., 2024. Biochar production under different pyrolysis temperatures with different types of agricultural wastes. Sci. Rep. 14 (1), 2625. https://doi.org/10.1038/s41598-024-52336-5.

Khedulkar, A.P., Dang, V.D., Thamilselvan, A., Doong, R.-a, Pandit, B., 2024. Sustainable high-energy supercapacitors: metal oxide-agricultural waste biochar composites paving the way for a greener future. J. Energy Storage 77, 109723. https://doi.org/10.1016/j.est.2023.109723.

Lewoyehu, M., Kohira, Y., Fentie, D., Addisu, S., Sato, S., 2024. Water hyacinth biochar: a sustainable approach for enhancing soil resistance to acidification stress and nutrient dynamics in an acidic nitisol of the northwest highlands of ethiopia. Sustainability 16 (13), 5537. https://doi.org/10.3390/su16135537.

Li, X., Yao, S., Wang, Z., Jiang, X., Song, Y., Chang, S.X., 2022. Polyethylene microplastic and biochar interactively affect the global warming potential of soil greenhouse gas emissions. Environ. Pollut. 315, 120433. https://doi.org/10.1016/j.envpol.2022.120433.

Miranda Zoppas, F., Sacco, N., Soffietti, J., Devard, A., Akhter, F., Marchesini, F.A., 2023. Catalytic approaches for the removal of microplastics from water: recent advances and future opportunities. Chem. Eng. J. Adv. 16, 100529. https://doi.org/10.1016/j.ceja.2023.100529.

Mulè, L., 2024. Revolutionizing waste management: the role of AI in building sustainable practices. ⟨https://aiforgood.itu.int/revolutionizing-waste-management-the-role-of-ai-in-building-sustainable-practices/⟩.

Ngo, T., Ranlaul, K., Ball, A.S., 2024. Enhanced methane production during the anaerobic digestion of chicken manure through the addition of pristine and recovered biochar. Clean. Waste Syst. 7, 100126. https://doi.org/10.1016/j.clwas.2023.100126.

Nguyen, V.G., Sharma, P., Ağbulut, Ü., Le, H.S., Cao, D.N., Dzida, M., Osman, S.M., Le, H.C., Tran, V.D., 2024. Improving the prediction of biochar production from various biomass sources through the implementation of eXplainable machine learning approaches. Int. J. Green. Energy 1–28. https://doi.org/10.1080/15435075.2024.2326076.

Nosratabad, N.A., Yan, Q., Cai, Z., Wan, C., 2024. Exploring nanomaterial-modified biochar for environmental remediation applications. Heliyon. https://doi.org/10.1016/j.heliyon.2024.e37123.

Olawade, D.B., Fapohunda, O., Wada, O.Z., Usman, S.O., Ige, A.O., Ajisafe, O., Oladapo, B.I., 2024. Smart waste management: a paradigm shift enabled by artificial intelligence. Waste Manag. Bull. 2 (2), 244–263. https://doi.org/10.1016/j.wmb.2024.05.001.

Qin, C., Wang, H., Yuan, X., Xiong, T., Zhang, J., Zhang, J., 2020. Understanding structure-performance correlation of biochar materials in environmental remediation and electrochemical devices. Chem. Eng. J. 382, 122977. https://doi.org/10.1016/j.cej.2019.122977.

Romero-Güiza, M.S., Flotats, X., Asiain-Mira, R., Palatsi, J., 2022. Enhancement of sewage sludge thickening and energy self-sufficiency with advanced process control tools in a full-scale wastewater treatment plant. Water Res. 222, 118924. https://doi.org/10.1016/j.watres.2022.118924.

Saharudin, D.M., Jeswani, H.K., Azapagic, A., 2024. Biochar from agricultural wastes: Environmental sustainability, economic viability and the potential as a negative emissions technology in Malaysia. Sci. Total Environ. 919, 170266. https://doi.org/10.1016/j.scitotenv.2024.170266.

Samuel Olugbenga, O., Goodness Adeleye, P., Blessing Oladipupo, S., Timothy Adeleye, A., Igenepo John, K., 2024. Biomass-derived biochar in wastewater treatment- a circular economy approach. Waste Manag. Bull. 1 (4), 1–14. https://doi.org/10.1016/j.wmb.2023.07.007.

Senthil, C., Lee, C.W., 2021. Biomass-derived biochar materials as sustainable energy sources for electrochemical energy storage devices. Renew. Sustain. Energy Rev. 137, 110464. https://doi.org/10.1016/j.rser.2020.110464.

Shen, J., Huang, G., An, C., Xin, X., Huang, C., Rosendahl, S., 2018. Removal of tetrabromobisphenol A by adsorption on pinecone-derived activated charcoals: synchrotron FTIR, kinetics and surface functionality analyses. Bioresour. Technol. 247, 812–820. https://doi.org/10.1016/j.biortech.2017.09.177.

Sheng, Y., Shanmugam, S., Chinnathambi, A., Salmen, S.H., Ge, S., Xia, C., Brindhadevi, K., 2022. Feasibility of microalgal and macroalgal biomass co-digestion on biomethane production. Int. J. Hydrog. Energy 47 (88), 37394–37400. https://doi.org/10.1016/j.ijhydene.2021.12.202.

Soltani, N., Bahrami, A., Giebeler, L., Gemming, T., Mikhailova, D., 2021. Progress and challenges in using sustainable carbon anodes in rechargeable metal-ion batteries. Prog. Energy Combust. Sci. 87, 100929. https://doi.org/10.1016/j.pecs.2021.100929.

Spinti, J.P., Smith, P.J., Smith, S.T., 2022. Atikokan digital twin: machine learning in a biomass energy system. Appl. Energy 310, 118436. https://doi.org/10.1016/j.apenergy.2021.118436.

Sun, J., Jayakumar, A., Díaz-Maroto, C.G., Moreno, I., Fermoso, J., Mašek, O., 2024. The role of feedstock and activation process on supercapacitor performance of lignocellulosic biochar. Biomass Bioenergy 184, 107180. https://doi.org/10.1016/j.biombioe.2024.107180.

Ukoba, K., Jen, T.C., 2022. Biochar and application of machine learning: a review. Intech Open. https://doi.org/10.5772/intechopen.108024.

Vasseghian, Y., Nadagouda, M.M., Aminabhavi, T.M., 2024. Biochar-enhanced bioremediation of eutrophic waters impacted by algal blooms. J. Environ. Manag. 367, 122044. https://doi.org/10.1016/j.jenvman.2024.122044.

Wang, K., Remón, J., Jiang, Z., Ding, W., 2024. Recent advances in the preparation and application of biochar derived from lignocellulosic biomass: a mini review. Polymers 16 (6), 851. https://doi.org/10.3390/polym16060851.

Wang, X., Kumar, V., Kumari, A., Kuzmin, E., 2022. Impact of digital technology on supply chain efficiency in manufacturing industry. Digit. Transform. Ind. 347–371. https://doi.org/10.1007/978-3-030-94617-3_25.

Waqas, M., Nizami, A.S., Aburiazaiza, A.S., Jabeen, F., Arikan, O.A., Anees, A., Hussain, F., Javed, M.H., Rehan, M., 2023. Unlocking integrated waste biorefinery approach by predicting calorific value of waste biomass. Environ. Res. 237, 116943. https://doi.org/10.1016/j.envres.2023.116943.

Wei, J., Huang, G., An, C., Yu, H., 2011. Investigation on the solubilization of polycyclic aromatic hydrocarbons in the presence of single and mixed gemini surfactants. J. Hazard. Mater. 190 (1-3), 840–847. https://doi.org/10.1016/j.jhazmat.2011.04.019.

Yaashikaa, P.R., Kumar, P.S., Varjani, S., Saravanan, A., 2020. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnol. Rep. 28, e00570. https://doi.org/10.1016/j.btre.2020.e00570.

Yang, Y., Tang, S., Chen, J.P., 2024. Carbon capture and utilization by algae with high concentration CO2 or bicarbonate as carbon source. Sci. Total Environ. 918, 170325. https://doi.org/10.1016/j.scitotenv.2024.170325.

Zhang, X., Zhang, X., An, C., Wang, S., 2023. Electrochemistry-enhanced peroxymonosulfate activation by CoAl-LDH@ biochar for simultaneous treatment of heavy metals and PAHs. Sep. Purif. Technol. 311, 123341. https://doi.org/10.1016/j.seppur.2023.123341.

Zhou, Y., Gao, J., Yang, X., Ni, H., Qi, J., Zhu, Z., Yang, Y., Fang, D., Zhou, L., Li, J., 2024. Recent progress in sludge-derived biochar and its role in wastewater purification. Sustainability 16 (12), 5012. https://doi.org/10.3390/su16125012.