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Transforming rice straw waste into biochar for advanced water treatment and soil amendment applications

Jagpreet Singh[a,b], Monika Bhattu[b,c], Rock Keey Liew[d], Meenakshi Verma[e], Satinder Kaur Brar[f,*], Mikhael Bechelany[g,h], Rajendrasinh Jadeja[a,*]

[a] Faculty of Engineering & Technology, Marwadi University, Rajkot-Morbi Road, Rajkot, Gujarat 360003, India
[b] Department of Chemistry, Research and Incubation Centre, Rayat Bahra University, Mohali, Punjab 140103, India
[c] Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab 140417, India
[d] NV Western PLT, No 208B, Second Floor, Macalister Road, Georgetown, Penang 10400, Malaysia
[e] Department of Applied Science, Chandigarh Engineering College, Chandigarh Group of Colleges Jhanjeri, Mohali, Punjab 140307, India
[f] Department of Civil Engineering, Lassonde School of Engineering, York University, Toronto, ON M3J 1P3, Canada
[g] Institut Européen des Membranes, IEM, UMR-5635, University of Montpellier, ENSCM, CNRS, Place Eugène Bataillon, CEDEX 5, Montpellier 34095, France
[h] Gulf University for Science and Technology, GUST, Hawally 32093, Kuwait

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ABSTRACT

The global rice industry produces an estimated 700 million tonnes of rice straw annually, with more than 100 million tonnes being burned openly in the fields. This practice significantly contributes to air pollution and greenhouse gas emissions. Each kilogram of burned straw releases approximately 0.29–0.38 kg of CO_2-equivalents, posing substantial environmental and public health risks, such as respiratory and cardiovascular diseases. In order to tackle these challenges, it is essential to focus on creating new, cost-effective, and sustainable approaches for managing rice straw. This review comprehensively examines the recent advances in the valorization of rice straw, focusing on production, optimization (surface area, pore structure, surface functional groups, and modification techniques), and application of rice straw biochar (RSBC) for wastewater treatment and soil amendment applications. Further, this study explored the composition and morphological analysis of rice straw, along with its management strategies, highlighting their merits and demerits. In addition, this review delves into the benefits of integrating RSBC into biofuel production, particularly in reducing methane emissions. Notably, it also discusses the advantages of utilizing leftover digestate (a by-product of biofuel production), which can be further processed into biochar, thus adding value to environment restoration. Therefore, this review guides future researchers to optimize RSBC properties, enhance biochar and digestate potential, and scale up for broad environmental applications within circular economy principles.

1. Introduction

Rice cultivation is incredibly important for maintaining global food security particularly in nations such as India, where it serves as a dietary staple for a large portion of the population. According to statistics from the Food and Agriculture Organization, global rice

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* Corresponding authors.
E-mail addresses: satinder.Brar@lassonde.yorku.ca (S.K. Brar), rajendrasinh.jadeja@marwadieducation.edu.in (R. Jadeja).

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production amounts to an impressive 756.74 million tonnes, generating approximately 700 million tonnes of rice straw and husks (Bhattacharyya et al., 2021). Regrettably, a mere 20 % of the rice straw is used, leading to over 100 million tonnes being burned annually due to delays in sowing the next crop (Singh et al., 2024).

As one of the largest global rice producers, India encounters a significant challenge in managing the extensive amount of rice straw generated after each harvest. The critical need to utilise the agricultural land for next crop leads to the open-field burning, which give rise to severe air pollution, soil degradation, and detrimental health effects (AMK, 2020). Beyond India, rice-producing countries worldwide suffer similar challenges, collectively contributing to a global environmental concern (Kumar et al., 2019). The combustion of rice straw results in the emission of a wide range of pollutants, including particulate matter, greenhouse gases, and harmful chemicals, into the atmosphere. This process contributes to air quality degradation and impacts climate change (Tipayarom and Oanh, 2007). Additionally, improper rice straw disposal in water bodies leads to water pollution, negatively impacting aquatic ecosystems and compromising the availability of clean water (Chen et al., 2008). The release of detrimental pollutants such as $PM_{2.5}$ and CO poses significant health risks to rural and urban populations, particularly respiratory issues, cardiovascular diseases, and other health complications associated with rice straw burning (Lorn et al., 2022). Moreover, the burning of rice straw in traditional practices leads to economic consequences, as potential resources that could otherwise be utilised for sustainable purposes are lost. Despite the cost-effectiveness, ease of tillage, and weed reduction benefits in subsequent crops, open burning releases greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O, as well as other trace gases. This negatively impacts human health and contributes to the potential for global warming (Fig. 1) (Romasanta et al., 2017).

Instead of common perceptions that GHG emissions from burning are lower than those from fresh straw incorporation, comprehensive assessments considering CO_2 emissions reveal that the immediate loss of a significant percentage of carbon (C) makes the global warming potential of burning comparable to that of incorporating fresh straw. Recognising the economic value of rice straw and exploring alternative uses could not only address environmental concerns but also generate avenues for income generation (Kaur and Singh, 2024; Lohan et al., 2018). Hence, addressing the management of rice straw is of utmost importance due to its widespread production globally, its significant environmental impact, and the necessity to shift towards more sustainable and environmentally friendly practices (Mittal et al., 2009; Zhang et al., 2013). These efforts are crucial for mitigating adverse consequences on soil quality, human health, and overall environmental well-being. Some innovations in agriculture such as zero emission-till farming and developing rice varieties with shorter straw length can mitigate the generation of excess straw. Moreover, promoting alternative uses like bioenergy production, animal fodder, and material for sustainable packaging can turn rice straw into a valuable resource. Numerous countries have recently implemented bans on open burning, promoting alternative methods such as incorporating fresh straw into the soil, baling for various purposes, and using straw for electricity generation, composting, or biochar (BC) production (Van Hung et al., 2019).

Among all the applications, BC production has been considered the most efficient and sustainable approach towards rice straw management. BC production leads to the complete conversion of rice straw into value-added products and meets all the requirements of sustainable development. Rice straw is notable for its high silica content, which is primarily found in the form of phytoliths. When rice straw is subjected to pyrolysis to create biochar, these phytoliths do not simply disappear. Instead, they remain embedded within the biochar matrix. During this process, the silica becomes even more concentrated and is intricately integrated with the carbon structure of the biochar. This unique silica-rich composition significantly enhances the stability of the resultant rice straw biochar (RSBC). Additionally, it augments its adsorption capabilities and imparts slow-release properties for silicon, making RSBC particularly advantageous for a range of environmental and agricultural applications. This enhanced biochar can improve soil health, enhance nutrient retention, and provide essential silicon to crops over time.

Substantial review articles have been published thus far, focusing either on the application of rice straw BC for analysis removal or on alternative management techniques for rice straw (Table 1). This review article is intended to provide a comprehensive evaluation of both conventional and advanced management strategies utilised for rice straw, with a specific emphasis on outlining the advantages

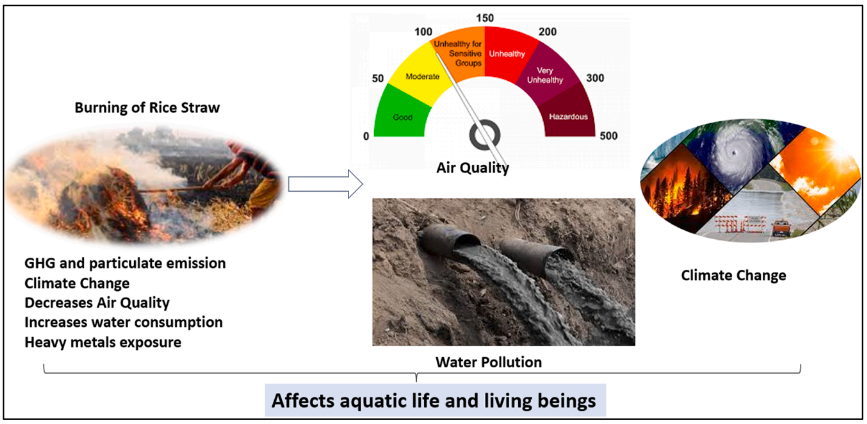


Fig. 1. Harmful impacts of rice straw burning.

and limitations of these methods with a detailed overview of the literature survey. Additionally, the manuscript highlights the significance of BC preparation over other management strategies, particularly in water remediation applications. Furthermore, it explores various removal and degradation techniques, offering detailed mechanistic insights into these processes. The review article not only covers the BC preparation from waste rice straw but also emphasizes the digestate leftover after the conventional utilization of rice straw with an emphasis on current challenges and future perspectives in this field. In this context, Fig. 2 provides a schematic representation of the review's structure, outlining the logical flow and organization of the paper.

2. Compositional and morphological analysis of rice straw

Rice straw originating from a group of Si-accumulating plants, contains significant amounts of silica (SiO_2) stored within specialized cell structures known as phytoliths. These phytoliths contribute rigidity and support to the plant's cellular matrix, making up 10–20 % of the total mass of rice straw. They are embedded in the lignocellulosic structure alongside cellulose, hemicellulose, and lignin (Bhattacharyya et al., 2021; Li and Delvaux, 2019). The elevated silica content is a distinguishing feature of rice straw compared to other crop residues which endowing its biochar derivative with unique properties (Chen et al., 2021; Xiao et al., 2014).

During the pyrolysis process, the organic components of rice straw, primarily cellulose and hemicellulose undergo significant thermal decomposition and volatilization. As these organic materials break down, they release gases which would have led to a silica concentrated within the resultant biochar matrix. The transformation during this process causes the silica that originally present in an amorphous state to develop into more crystalline structures, particularly when subjected to higher pyrolysis temperatures. The resulting biochar that rich in this silica and carbon interwoven structure further establishes a robust and resilient framework. This unique composition significantly enhances the stability, adsorption capacity, and overall functionality of the biochar, making it highly effective for various environmental applications (Xiao et al., 2014).

The retention of silica phytoliths in rice straw-based composites (RSBC) is particularly advantageous in soil and environmental applications due to the slow-release characteristics of silicon. Research has demonstrated that RSBC can serve as a sustained source of bioavailable silicon, thereby enhancing soil nutrient balance, promoting plant growth, and aiding in the mitigation of soil desilication

Table 1

Comparison of recent studies published on rice straw BC for water remediation.

Title	Composition analysis	Management techniques	BC advantage	Adsorption	Degradation	Ref.
Biochar derived from rice by-products for arsenic and chromium removal by adsorption: a review	x	x	√	√	x	(Chatzimichailidou et al., 2023)
Recent trends, opportunities and challenges in sustainable management of rice straw waste biomass for green biorefinery	x	√	√	x	x	(Rathour et al., 2023)
Rice straw management through biofuel, biochar, mushroom cultivation, and paper production to overcome environmental pollution in North India	√	√	√	x	x	(V. Kumar et al., 2023)
Rice husk and rice straw-based materials for toxic metals and dyes removal: a comprehensive and critical review	√	x	√	√	x	(Sahoo et al., 2023)
Production of biochar from rice straw and its application for wastewater remediation — An overview	x	x	√	√	x	(Foong et al., 2022)
Preparation and characterization of biochar from rice straw and its application in soil remediation	x	√	√	x	x	(El-Hassanin et al., 2020)
Review on rice husk biochar as an adsorbent for soil and water remediation	x	x	√	x	x	(Li et al., 2023)
Application of biochar for the remediation of polluted sediments	x	x	√	√	x	(Yang et al., 2021)
Alternative uses of rice straw in north-western regions of India: a review	x	√	√	x	x	(Shukla et al., 2022)
Biochar and engineered biochars for water and soil remediation: a review	√	x	x	√	x	(Islam et al., 2021)
Rice industry by-products as adsorbent materials for removing fluoride and arsenic from drinking water—a review	x	x	√	x	x	(Collivignarelli et al., 2022)
Biochar for environmental sustainability in the energy-water-agroecosystem nexus	x	x	√	x	√	(Malyan et al., 2021)
Conversion of biological solid waste to graphene-containing biochar for water remediation: A critical review	x	x	√	x	√	(Fang et al., 2020)
This work	√	√	√	√	√	

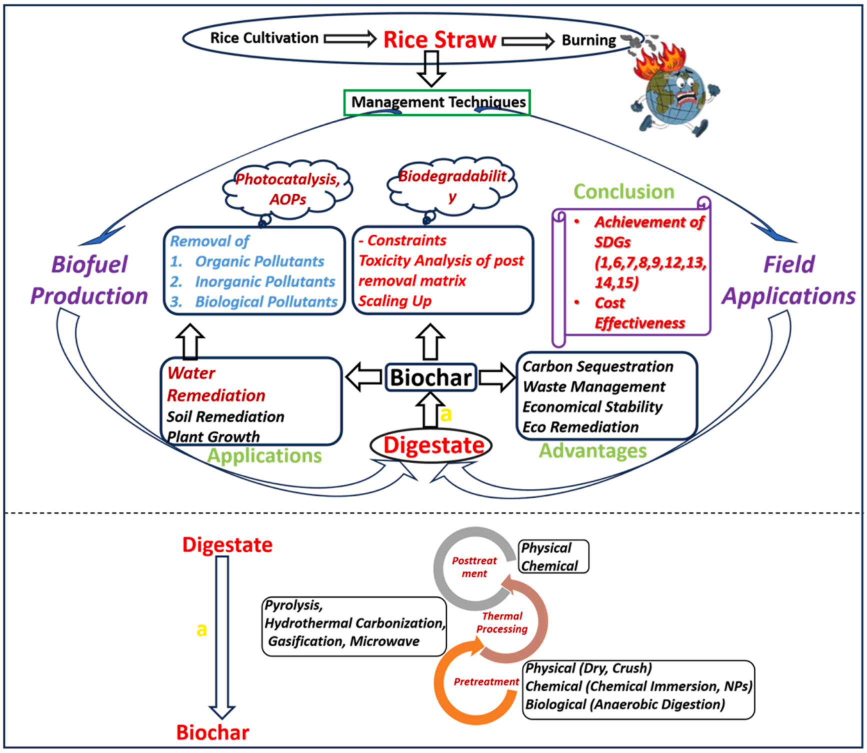


Fig. 2. Schematic representation of the review's structure, outlining the logical flow and organization of the paper.

within agricultural systems (Li and Delvaux, 2019). This is especially significant for paddy fields and other silicon-depleted soils, where the presence of silicon has been found to bolster crop resilience to stress, increase yields, and improve soil structure (Chen et al., 2021).

Although rice straw offers substantial challenges owing to its variable phytochemical composition depending on several parameters including rice variety, seasonal fluctuations, climatic circumstances, and geographic location. However, the phytoconstituents present in straws offer various advantageous functionalities towards environmental remediation and to achieve SDGs. Hence, the complete knowledge of chemical composition is a crucial parameter for efficient valorisation alone or in combination with other biomasses. The major components of rice straw are lignin (5–24 %), hemicellulose (19–27 %), and cellulose (32–47 %) [5,10]. Lignin is a major

Table 2
Different compositional, morphological, and structural characterizations techniques for rice straw.

Analysis	Instrument	Parameters	Outcomes	Ref.
Compositional	TGA	Cellulose, Hemicellulose, and Lignin	32–47 %, 19–27 %, and 15–24 %, respectively	(Singh et al., 2024)
	AAS, and LCMS	Ash, Silica, Pactin, Glucose, Galactose,Mannose, Xylose and Arabinose	18.8 %, 14 %, 2.3 %, 40–43 %, 0.4 %, 1.8 %, 14.8–19.3 %, and 2.7–4.5 %, respectively	
Morphological and structural	SEM Analysis	Topography and morphological	Carbon skeleton with pores of irregular shape and different sizes	(Chen et al., 2021)
	XRD Analysis	Crystal Structure	Confirms the presence of amorphous and graphitic carbon ascribed by $2\theta = 22.48°$ and 43.0° corresponds to 002 and 100 crystal planes of carbon	(Xu et al., 2022)
	Raman Spectroscopy	Structural defects and graphitization	Confirms the presence of defective structural and graphitic carbon with two peaks at 1345 (D band) and 1598 cm^{-1} (G band), respectively.	(Wang et al., 2020)
	FTIR Spectroscopy	Molecular structure and Functional Groups	Vibrational peaks at 3424, 1617, 1104, and 804 cm^{-1} corresponds to O–H, C═C/C═O, C–O, and C–H groups, respectively	(Xu et al., 2022)
	XPS	Electronic states and chemical compositions	C 1 s = 3 peaks (287.6, 285.9, and 284.8 eV correspond to the C═O, C-O, and C═C/C-C, respectively) O 1 s = 2 peaks (532.4 and 533.5 eV correspond to the C═O and C-O, respectively)	(Qin et al., 2022)

component of rice straw containing aromatic alcohols (p-coumaryl, coniferyl, and sinapyl). Lignin strengthens the cell wall in plants by forming a compound with carbohydrates and phenolics. The composition of the cell walls in rice straw contains 63 % of carbohydrates, 27 % lignin, 2 % uronic acids, 4 % acetyl content, 4 % trans-p-coumaric acid, and less than 1 % trans-ferulic acid [14]. Interestingly, rice straw has larger quantities of esterified and etherified forms of p-coumaric and ferulic acids than corn and wheat straw. Rice straw lacks nitrogen, whereas it contains valuable ash (> 10 %), which is mostly made up of < 15 % alkali content and ~75 % SiO_2. The characterisation of straws was performed using various microscopic, thermal, and spectroscopic techniques as illustrated in Table 2.

When crop straws are exposed to high temperatures, the biomass matrix dissociates, releasing volatile gases and forming a porous charcoal structure known as straw-based BC (RSBC). The porosity and surface area of BC is significantly influenced by the temperature at which it is produced through pyrolysis. When the temperature exceeds 1000 °C, it can cause the breakdown of cell structures, resulting in a decrease in both porosity and surface area (Cetin et al., 2004). The pore structure of BC is a crucial factor influencing its adsorption capacity(Fu et al., 2012). Remarkably, it has been observed that the pore volume of straw-derived BC increases with higher pyrolysis temperatures. Notably, a significant proportion of micropores (approximately 80 %) are found within a pH range of 5.5–11, with electrical conductivity (EC) ranging from 4 mS/cm to 8 mS/cm (Igalavithana et al., 2017; Kumar and Bhattacharya, 2021). A higher pH is usually the consequence of higher synthesis temperatures because they cause the volatilisation of organic acids following thermal treatment, remove acidic surface groups, and increase ash content. Together, these elements raise the BC's alkalinity (Fidel et al., 2017). On the other hand, hemicellulose breaks down at lower pyrolysis temperatures, producing acetic, formic, and propionic acids that raise the pH level of acidity (Kumar and Bhattacharya, 2021). Furthermore, the cation exchange capacity (CEC) of BC ranges from 8 to 60 cmol/kg and generally decreases with rising production temperatures. This reduction is due to the formation of aromatic carbon and the loss of functional groups from the surface of the BC (Wu et al., 2012). Additionally, BC produced from biomass with a greater ash content often has higher CEC values because the biomass's alkali metals help in the formation of functional groups that contain oxygen, which raises the CEC of BC (Tag et al., 2016). All the aforementioned characteristics (Fig. 3) of the rice straw made it an efficient platform for re-utilization not only for management issues but also for sustainable development. In this regard, various kinds of management techniques were followed from an early age via using it for animal fodder, however, nowadays much-advanced techniques are also employed to mitigate the malpractice in managing the rice straw.

3. Rice straw management strategies

3.1. Conventional technologies

3.1.1. Straw mulching

This is a widely used farming technique that involves even distributing chopped rice straw throughout fields before the growth of subsequent crops. This approach was highly advantageous for agricultural operations as it elevates soil aeration, minimises evapotranspiration and weed pressure, regulates soil temperature, and increases root penetration resistance (Fig. 4). These benefits ultimately support persistent crop productivity (Qin et al., 2016; Sharma et al., 2011). Additionally, mulching helps retain soil moisture, decreases soil evaporation, and enhance water retention, especially in the early phases of plant production. Remarkably, applying mulch made of rice straw to winter wheat has reduced soil evaporation and water retention potential by 40 mm and 10 %, respectively (Zhang and Oweis, 1999). Furthermore, it has been demonstrated that applying rice mulch to wheat crops can save a considerable quantity of irrigation water, offering a potential solution to the problem of water stress in agriculture [24].

The application of decomposed straw mulch has been found to significantly enhance soil nutrients such as N, P, and K while increasing organic matter content. This in turn leads to improved soil quality and water conservation. Variations in mulch size have shown a notable reduction in soil loss, effectively minimising runoff. Furthermore, the use of a straw cover on the surface of the soil inhibits weed growth by limiting light absorption and impeding their ability to photosynthesise, thus improving nitrogen utilisation efficiency. Despite these benefits, challenges such as high labour costs, difficulties in machine rice harvesting, and associated storage and transportation costs due to limited financial incentives, as well as a lack of comprehensive farmer knowledge, need to be addressed

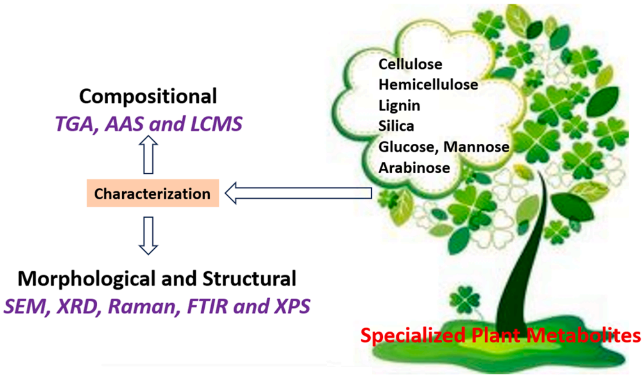


Fig. 3. Different kinds of characterisation techniques for rice straw.

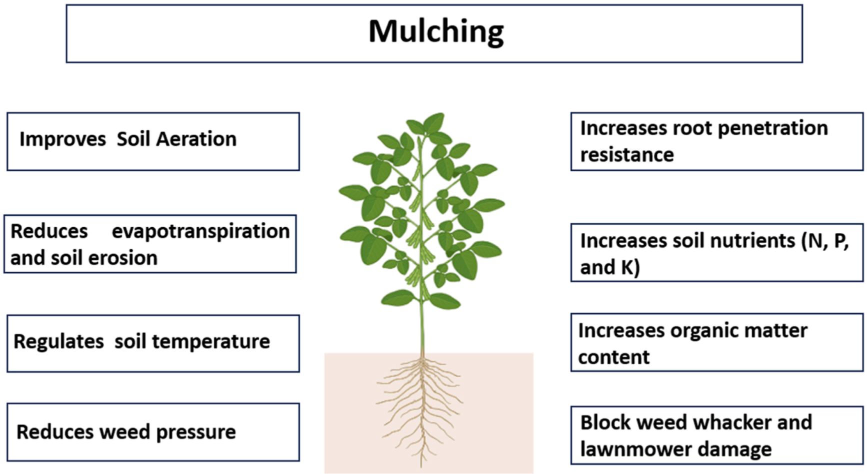


Fig. 4. Advantages of Straw mulching.

to maximise the efficacy of these techniques (Bhattacharyya et al., 2021).

3.1.2. *Agricultural practices*

Rice straw has been widely utilised for animal feeding, mushroom cultivation, composting, and animal bedding. In Southeast Asia, rice straw is a common dry feed source particularly in the dry season due to the imbalanced compositional constituents (lack of P, Fe, Mn, and Na and abundance of K, Ca, and Mg), low digestibility and high crude protein. Despite its several advantages, animals do not prefer rice straw due to the lack of digestive enzymes required for its digestion, particularly by ruminants. Furthermore, environmental aspects such as temperature, pH, and genetic variation impact the digestibility of rice straw. Various methods, including physical (e.g., chopping, grinding, soaking), chemical (e.g., urea, ammonia, sodium hydroxide), and biological treatments (microbial action), were explored to enhance the efficacy of rice straw. These treatments aim to increase nutrient availability for animal feeding by reducing straw size, weakening the lignocellulosic structure, and promoting microbial breakdown.

Moreover, RS behaves as a substrate for mushroom development due to high lignocellulose content, which is easily broken down by extracellular enzymes secreted by the mycelium of the mushroom such as β-glucosidase, endoglucanase, laccase, and xylase (E. and D., 2015). Growing edible mushrooms in rice straw has been considered one of the biologically sound methods for managing rice straw and turning it into a valuable product (Singh and Patel, 2022). As a result of their effective uptake of nutrients and energy, mushrooms grow mycelially and produce fruiting bodies (Bhattacharyya et al., 2020).

Additionally, composting rice straw has significant promise for effectively using rice straw and other organic waste. Effective composting requires a C:N content (20–30) which can be reached by mixing rice straw with animal waste (Vigneswaran et al., 2016). The kinetics of the composting are greatly influenced by the physicochemical characteristics of the source materials as well as variables like pH, moisture, temperature, and microbial variety (Van Hung et al., 2019). Composting presents an energy-efficient approach for repurposing wet rice straws within agricultural contexts instead of allocating them to food production or animal feed. Apart from composting, limited viable applications exist for rice straw remnants from mushroom farming or the by-products of biogas and bioethanol production. This process converts discarded rice straw into nutrient-rich compost suitable for agricultural use, thereby reducing the dependency on synthetic fertilizers. Furthermore, various studies have highlighted the positive impact of using rice straw bedding on multiple aspects of cattle farming. This includes observed enhancements in milk production and quality and animal reproduction. The implementation of rice straw bedding not only ensures the welfare of the animals but also contributes to optimising agricultural practices for increased productivity and animal health.

In summary, the versatile utilization of rice straw in agricultural applications offers substantial environmental and economic advantages, particularly in its use as mulch and compost, as well as its role in mushroom cultivation and animal bedding. The practice of rice straw mulching enhances soil health by increasing nutrient levels, reducing evaporation, and improving water efficiency, all of which contribute to sustainable crop production. Despite challenges such as labour costs and limited financial incentives, incorporating rice straw into farming systems presents a promising solution for addressing soil degradation and water scarcity. Furthermore, its application in animal husbandry and as a substrate for mushroom cultivation underscores the adaptability of rice straw in promoting more efficient and productive agricultural practices. By surmounting existing obstacles and maximizing the use of rice straw, its potential to bolster farm sustainability and productivity is evident.

3.2. *Advanced technologies based on production of renewable sources*

3.2.1. *Bioethanol production*

Bioethanol (CH_3CH_2OH or EtOH) is an oxygenated biofuel that offers a viable transportation alternative. Its high-octane content makes it more desirable than other liquid fuels. Biorefinery-based production is more lucrative than other conventional approaches [29]. According to Singh et al. (2016), ethanol production plants based on rice straw with a 24-million-litre capacity release fewer greenhouse gases (GHGs) due to this strategy than a 10 MW thermal power plant(Singh et al., 2016). Bioethanol contains about 35 % oxygen that can help minimise particle and NO_x emissions during burning. Pre-treatment, fermentation, and enzyme hydrolysis are the major steps for EtOH formation (Tayyab et al., 2018). Effective pre-treatment procedures seek to lower the crystallinity of RS cellulose, break lignin-cellulose connections, and reduce the particle size to maximise hydrolysis for the manufacturing process (Wu et al., 2020).

The conversion of rice straw into bioethanol is a significant advancement in renewable energy technologies which offers a prominent and most sustainable alternative to traditional fossil fuels. This process mitigates greenhouse gas emissions and leverages agricultural waste, transforming it into a valuable energy resource. The high oxygen content in bioethanol contributes to cleaner combustion, thereby reducing particulate and NO_x emissions, both of which are major contributors to air pollution. The biorefinery approach enhances bioethanol production is economic viability, positioning it as a competitive alternative in the energy market. However, the efficiency of bioethanol production heavily relies on the optimization of pre-treatment processes, which is crucial for breaking down the complex lignocellulosic structure of rice straw. Improved processes in this regard can significantly increase the overall yield and efficiency of bioethanol production, further solidifying its role as a renewable energy source. Despite these advancements, challenges related to the scalability and integration of bioethanol production into existing energy infrastructures still need to be addressed, necessitating attention to fully realize its potential as a fundamental component in the transition to sustainable energy.

3.2.2. *Biogas production*

Advancements in biogas production have been centred on refining the anaerobic digestion process and minimising methane emissions. Despite the historically notable methane emissions involved in rice straw decomposition, novel pre-treatment techniques such as steam explosion and chemical treatments (e.g., alkalisation and ammonization) have displayed the capacity to augment the efficiency of biogas generation. Although, the emerging method of biophotolysis for generating bio-hydrogen presents a sustainable and eco-friendly substitute for traditional energy sources. Continued exploration of these approaches is crucial for enhancing yields and rendering biogas production more economically feasible. Moreover, the shift from uncontrolled methane emissions to regulated biogas production through anaerobic digestion could play a pivotal role in reducing the carbon footprint of the agricultural sector.

Rice straw has been considered a major contributor towards methane production (approximately 25–150 t of methane annually, accounting for 15–40 % of total emissions) owing to the accumulation of leftover rice straw in fields (Glissmann and Conrad, 2000; James and James, 2010; Li et al., 2011). However, significant reductions in methane emissions have been observed when leftover rice straw is removed from fields instead of returned to them (Koga and Tajima, 2011). Anaerobic absorption of lignocellulosic rice straw can occur in either wet environments (with total solids less than 10 %) or dry environments (with total solids more than 10 %). However, digestion proceeds more swiftly in wet environments under similar conditions. Various pretreatment methods have been investigated to enhance methane production such as alkalisation, size reduction, steam explosion, ammonization, and fungal biodegradation (Wyman et al., 2005). Additionally, rice straw can produce bio-hydrogen, a promising and eco-friendly energy source. In a process known as biophotolysis, rice straw is treated with either 2 % H_2SO_4 or 2 % NaOH and the bacterium Proteus mirabilis is

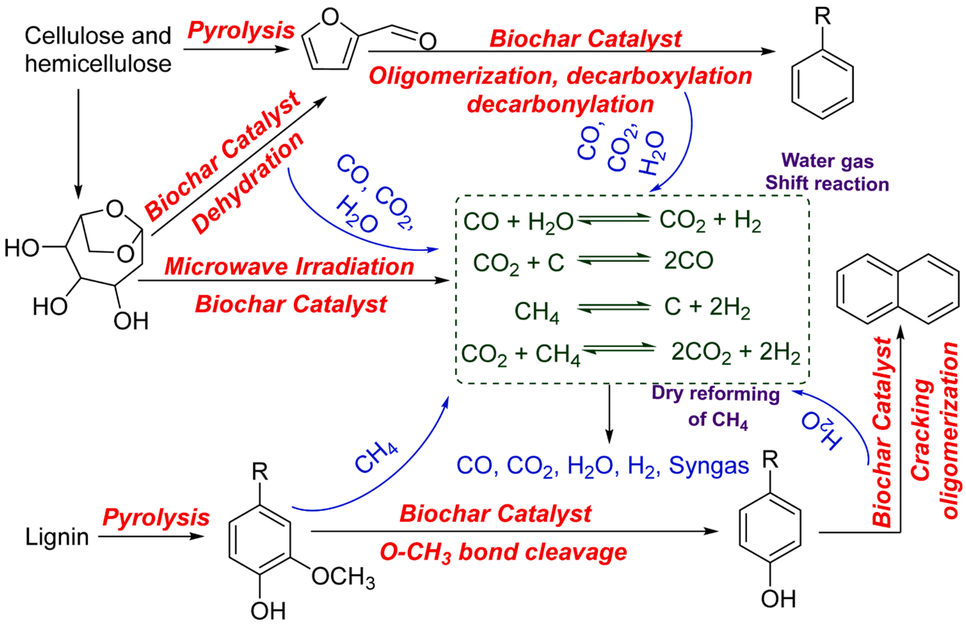


Fig. 5. Schematic illustration of conversion of cellulose, hemicellulose, and lignin into the mineralised components.

converted into bio-hydrogen (Mechery et al., 2021).

The utilization of rice straw as a renewable energy source, particularly for biogas and bioethanol production, demonstrates its potential to reduce greenhouse gas emissions and bolster energy sustainability substantially. While advancements in the conversion processes of rice straw into biofuels and biogas are being made, there are still challenges in optimizing these methods to ensure maximum efficiency and economic feasibility. Continued research and technological innovation are imperative in surmounting these obstacles, thereby facilitating the complete employment of straw as a sustainable energy precursor.

3.2.3. Bioenergy production

Crop residues are significant biomass sources and primary reservoirs for bioenergy production (Kargbo et al., 2010). The establishment of power plants utilising rice husk and straw worldwide offers a competitive alternative to fossil fuels for electricity generation in thermal power plants (Logeswaran et al., 2020; Suramaythangkoor and Gheewala, 2008). Depending on the method of burning, rice straw usually has a thermal efficiency of 60–75 %. However, there are a number of difficulties with implementing rice straw-based power plants, such as rusting, contamination, sintering, and slagging in the thermal power production system (Said et al., 2013). The high ash content of rice straw and its low melting point complicate the combustion process. The use of rice straw as biomass fuel faces significant challenges, primarily related to product consistency and logistical complexities (Y. Wang et al., 2023). Economic viability diminishes as transportation distances increase due to the added costs. Additionally, the cost of rice straw is influenced by several factors, including labour expenses, transportation fees, and farmer subsidies, all of which affect the financial sustainability of rice straw-based power generation plants. Enhancing the combustion uniformity of rice straw by shredding it from its baled form has been shown to improve its efficiency (Verma, 2014). The bioenergy sector is a substantial global employer, with approximately 3.2 million people engaged in various aspects of the bioenergy supply chain. The use of agricultural waste, such as rice straw, for electricity generation offers both economic and environmental benefits, including pollution reduction and the creation of employment opportunities in agro-based power plants. (Fig. 5).

Undoubtedly, efficient management techniques are essential for properly handling rice straw, with BC emerging as a leading method for its valorisation. During conventional management strategies, residual straw components persist in the environment, posing significant ecological risks. For instance, the residual straw fragments (sediments) can leach toxic compounds, adversely affecting

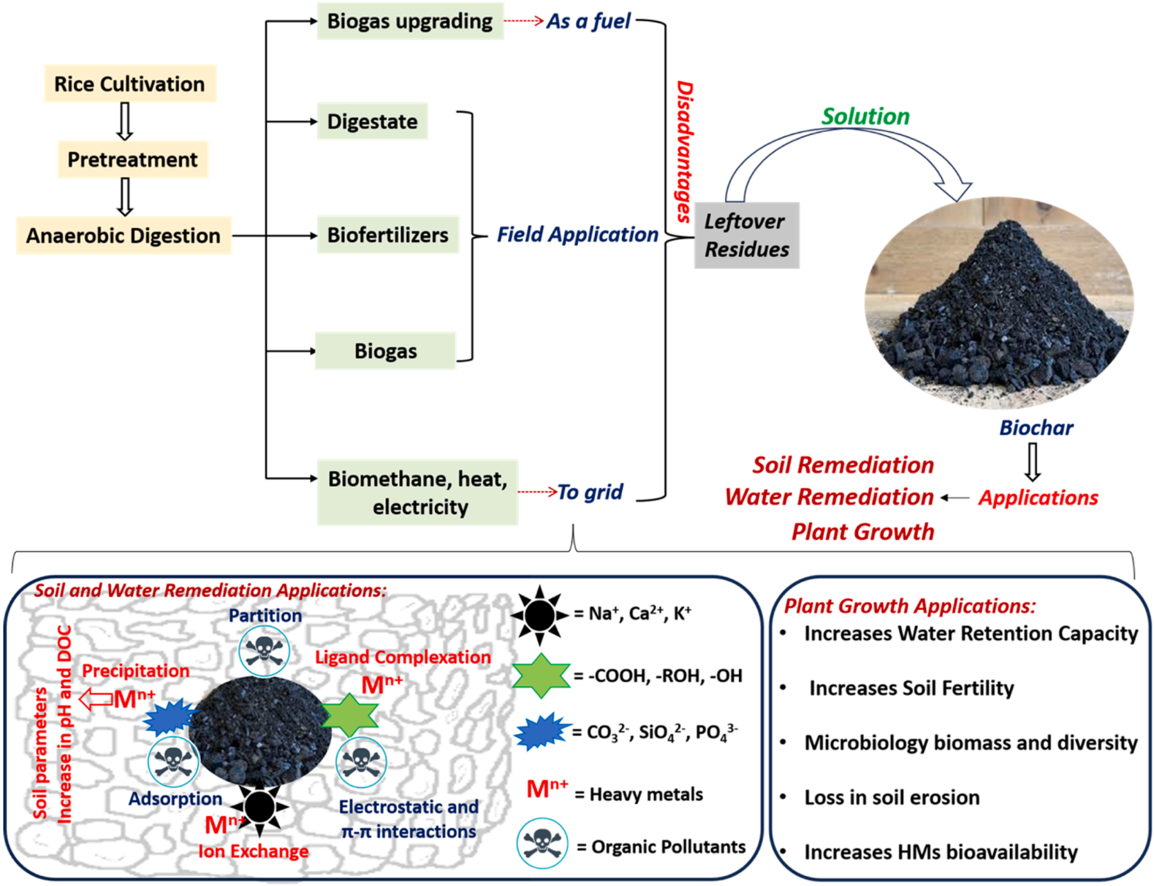


Fig. 6. Illustration of rice straw management techniques along with their diverse applications, disadvantages and their potential alternative with applications in environmental restoration.

environmental health (Yang et al., 2021). Moreover, residue left after biofuel production, often referred to as biofuel waste or biomass residue, is a valuable byproduct that can be managed through several alternative procedures including composting, anaerobic digestion; direct land application; and incineration. However, BC production is frequently preferred over other methods for several environmental and economic reasons. The first and foremost reason is the utilisation of BC enables the complete conversion of straw biomass into a beneficial carbonaceous material. BC derived from the pyrolysis of biowaste offers several distinct advantages over traditional carbon-based materials owing to its high surface area, catalytic potential, and favourable surface-to-volume ratio. There are various methods for synthesising BC, including pyrolysis, torrefaction, and gasification, which were already discussed in our previous work (Singh and Verma, 2024). Additionally, BC production is cost-effective and environmentally friendly, aligning with sustainable development objectives. Moreover, BC production mitigates harmful gas emissions, further enhancing its eco-friendly profile. Furthermore, BC finds extensive application in environmental remediation efforts, spanning water and soil treatment, as well as promoting plant growth. Its porous structure facilitates the retention and filtration of contaminants in water bodies and soils, thus improving overall environmental quality (Fig. 6).

In short, while crop residues such as rice straw offer significant potential as biomass sources for bioenergy production, establishing power plants utilizing rice straw presents considerable challenges. The high ash content, low melting point, and associated operational issues, namely sintering, slagging, and fouling, complicate the combustion process, adversely affecting the thermal efficiency and reliability of these facilities. Additionally, logistical concerns, particularly those related to transportation and product uniformity, markedly impact the economic viability of rice straw as a biomass fuel. Despite these challenges, using rice straw for BC production presents a promising alternative. BC provides a sustainable approach to managing agricultural waste and enhances environmental well-being through its applications in soil and water remediation. As the bioenergy sector continues to expand, addressing the technical and economic barriers to rice straw utilization will be vital in realizing its full potential as a renewable energy resource, thus contributing to energy sustainability and environmental conservation. Thus, its potential for long-term carbon sequestration, improvement of soil health, and pollutant removal makes it a highly preferred option, especially in sustainable and circular agricultural systems. The potential of rice straw mediated BC for water remediation is comprehensively explained in next section.

3.2.4. Preparation of RSBC

RSBC preparation includes various thermal degradation processes like pyrolysis, hydrothermal carbonization, and thermal gasification. All these processes lead to significant physical and chemical transformations of rice straw and are greatly affected by the temperature and heating rate which finalizes the properties of resulting RSBC. This transformation majorly consists of three stages *viz* i) dehydration Stage (<200°C); ii) devolatilization stage (200–500 °C); and iii) carbonization stage (>500°C)(Gabhane et al., 2020). The primary stage includes the evaporation of water at a lower temperature (<200°C) and after increasing the temperature beyond 200 °C, degradation of hemicellulose (200–300°C) and cellulose begins (300–400 °C). Lignin is the most stable among the three components and it decomposes over a broader temperature range (250–500°C). On further rising the temperature, BC undergoes aromatization which leads to the development of a highly stable, carbon-rich structure with graphitic domains (Fig. 7)(Guo et al., 2024).

Depending on the degradation criteria of rice straw at varying temperature, RSBC is prepared at different heating rates and residence time. For instance, pyrolysis is categorized into slow and fast pyrolysis which occurs at a heating rate of 0.02–1 °C/s and over 2 °C/s, respectively. Additionally, the residence time for slow pyrolysis ranges from a few hours to days, with a temperature range of 300–700 °C. In contrast, fast pyrolysis has shorter residence times of less than 10 seconds, and operates within a temperature range of 300–1000 °C. Moreover, hydrothermal carbonization (HTC) is another thermochemical process that employs water at elevated temperatures and pressures to convert biomass into hydro char. Unlike pyrolysis, HTC eliminates the need for pre-drying and produces hydro char with reduced moisture and volatile matter content, making it a promising method for various environmental applications. HTC typically operates at temperatures ranging from 200–250 °C for low-temperature carbonization and 300–400 °C for high-temperature processes, with residence times of 1–3 hours. Furthermore, the thermal gasification is another innovative approach combining bioenergy production with water remediation and soil fertility management(Foong et al., 2022). Hansen et al. (2015) produced biochar using low-temperature circulating fluidized bed (LT-CFB) and Two-Stage gasifiers. The LT-CFB system operated at 700–750 °C, while the Two-Stage system reached temperatures of 1000–1200 °C, with each stage independently managing pyrolysis and gasification. The gasification biochar showed a liming effect, raising soil pH levels and enhancing soil properties(Hansen et al., 2015).

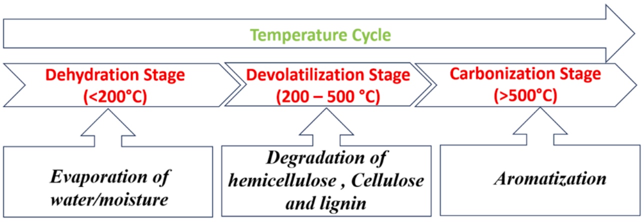


Fig. 7. Thermal degradation procedure for the RSBC synthesis over a temperature cycle of 20 – 1000 °C.

4. Applications rice straw biochar for environmental remediation

4.1. Adsorption process

Recently, rice straw BC has gained popularity for being the most affordable, efficient, and green adsorbent for wastewater treatment owing to its various advantages, including low cost, physicochemical features, high efficiency, ease of use, plentiful resource use, an abundance of functional groups, and high efficiency (Ajala et al., 2023; X. Zhang et al., 2023). The removal process includes a complex multi-step process in which transfer of contaminants from water to BC surface occurs either *via* diffusion as single/multi-layer or diffusion within the pores of BC (Krasucka et al., 2021). Contaminant diffusion is led to various interactions such as π-π, hydrophobic, charge-dipole, and electrostatic (Cheng et al., 2021; Dao et al., 2020; Liu et al., 2023; Qu et al., 2023).

The adsorption and removal efficacy are affected by numerous parameters, such as pore size, functionality, type of contaminant, and environmental parameters (pH/temperature) (Ajala et al., 2023). For instance, the contaminants containing–COOH, –NO_2, and –OH can easily form H-bonds with BC, and hence, the surface functionalisation is performed with specific emphasis on the selection of modifying agent, which facilitates the high possibility of interaction with the aforementioned groups of target contaminant (Kumar et al., 2022).

Moreover, pore size distribution and pore-filling effects were identified as crucial factors influencing the adsorption of contaminants, which facilitates the diffusion of pollutants to the inner surface (Stylianou et al., 2021; Jang et al., 2018). Additionally, the pH-dependent ionisation of contaminants influences electrostatic interactions. For instance, electrostatic repulsion occurs when the pH is beyond 3.4–7.6, reducing the adsorption efficacy of SBC due to similar charges between the surface of SBC and tetracycline molecules (Wang and Wang, 2018).

In the case of organic contaminants, interactions such as π-π and H-bonding contributes a crucial part in the adsorption of target analyte due to aromatic ring and functionalities such as–NO_2, –OH, and –COOH, respectively (Zhang et al., 2021). For instance, sulfonamide group is recognised for its strong electron-accepting properties, acting as a π-electron acceptor (Wang et al., 2022; Xu et al., 2022; Zhang et al., 2021). Raman spectroscopy was employed to detect π-π interactions, with shifts in Raman peaks indicating the occurrence of these interactions and charge transfer during adsorption on BC (Qin et al., 2022; Xu et al., 2022). Although BC has been applied for the recalcitration of numerous contaminants, its removal efficiency often falls short of expectations. To enhance the adsorption capacity of the BC, various modifications have been implemented, including physical, chemical, biological, and hybrid treatment, to improve its overall performance.

The biological modification involves the enhancement of microbial capability on the BC surface. These modifications present the benefits of low energy consumption and absence of byproduct formation. Nonetheless, it is noteworthy to point that this strategy does require a longer time to complete. As a result, these methods are not the most favoured (Meenakshisundaram et al., 2021). Conversely, physical modifications are utilised to enhance the physicochemical characteristics of BC including pore distribution, surface area, and aromatic behaviour. These modifications involve steam modification and ball milling, which improves the pore volume and specific surface area. The ball milling process is well known for its sustainable nature and low energy consumption (Kumar et al., 2020).

Chemical modifications involve acid/base modification or impregnation with a specific chemical component depending on the target analyte and are considered the most effective compared to other modification techniques (Kumar et al., 2022). For example,

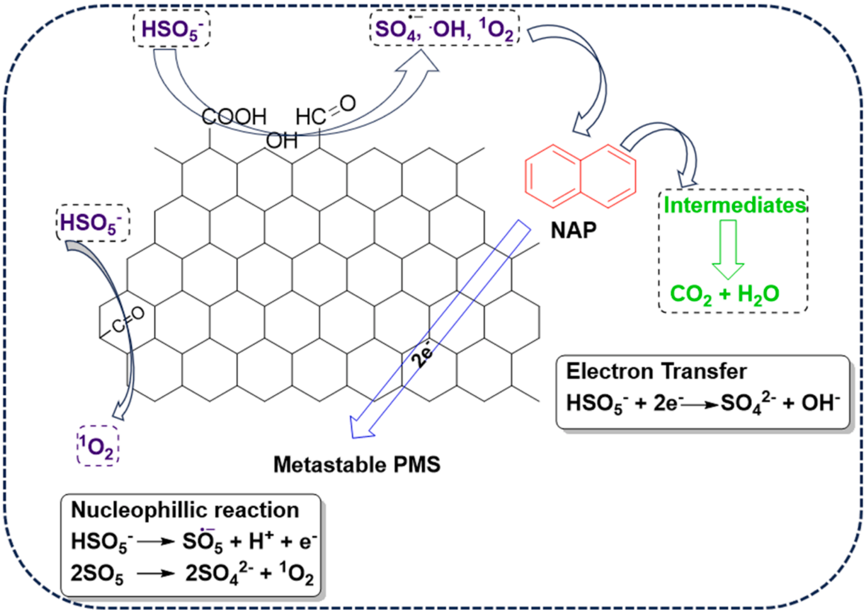


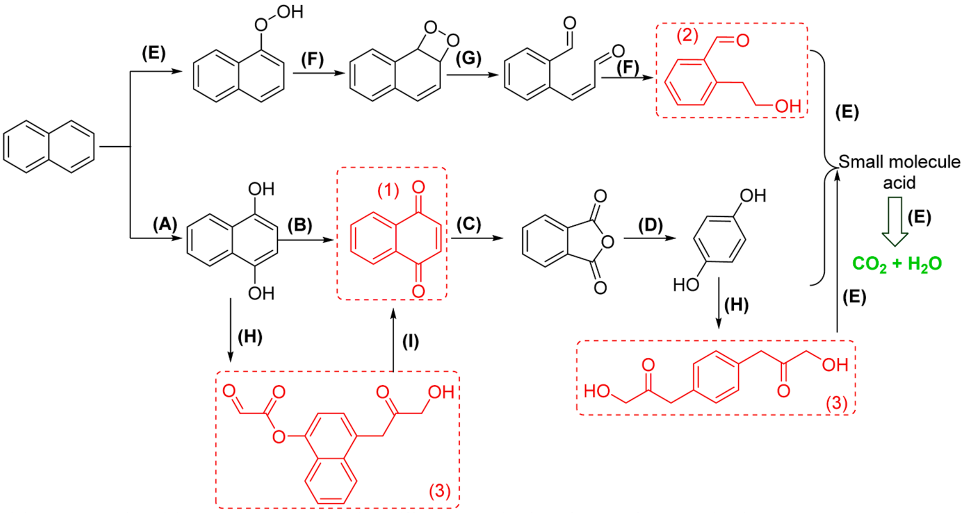
Fig. 8. Synergistic effect of activation and adsorption of naphthalene on BC900 surface.

alkali modification increases the nitrogen-component groups, whereas acid enhances the amount of oxygen-component groups (Wang and Wang, 2019). Potassium hydroxide (KOH) is the most effective among various bases due to outstanding intercalation and catalytic potential (Sangon et al., 2018).

In 2023, Zhang *et al.*, employed RSBC as a peroxymonosulfate (PMS) activator to remove naphthalene from water (J. B. Zhang et al., 2023). BC was synthesised at varying temperatures, with BC produced at 900 °C (BC900) demonstrating the highest activation potential and removal efficiency across a broad initial pH range (5–11). The best efficiency of BC900 was due to the generation of reactive species, including singlet oxygen ($^1O_2$), hydroxyl radicals (•OH), and sulfate radicals (SO_4•-), through persulfate activation, along with efficient electron transfer. The mitigation of naphthalene was driven by the synergistic effects of both activation and adsorption onto the BC900 surface (Fig. 8). Optimal activation and removal were achieved with 0.5 g/L BC900 and 10 mM PMS. Additionally, quenching experiments using methanol (MeOH), tert-butanol (TBA), furfuryl alcohol (FFA), and p-benzoquinone (PBQ) suggested that $^1O_2$ is the primary reactive species facilitating the naphthalene degradation, while SO_4•-, •OH, and O_2•- played negligible roles in the process(J. B. Zhang et al., 2023).

Moreover, a thorough evaluation of the toxicity of the degraded products was also conducted. Initially, two possible pathways were predicted to determine the degraded products depending on the exposure of reactive species which were further confirmed using HPLC-MS. In Pathway I, the α-carbon of naphthalene undergoes hydroxylation upon exposure to $SO_4^{\bullet-}$ and $^\bullet$OH, resulting in the formation of 1,4-p-naphthol. Subsequent reciprocal isomerisation transformed 1,4-p-naphthol into 1,4-p-naphthoquinone (A, m/z = 158). Throughout the degradation process, 1,4-p-naphthol and p-phenol were susceptible to esterification with low molecular weight acids, yielding compounds C (m/z = 226) and D (m/z = 276), as reported by Yang et al. in 2018(Yang et al., 2018). In Pathway II, the attacking species $^1O_2$ and $O_2^{\bullet-}$ induced the formation of the transient α-peroxy naphthalene (B, m/z = 150). These intermediates were prone to further oxidation, ultimately resulting in the formation of small molecule acids CO_2, and water H_2O (Fig. 9). The intermediates formed during the degradation were reported as toxic. Hence, toxicity analysis was performed using *Stenotrophomonas maltophilia* to analyse their impact on microbial growth. The bacterial growth was negligibly inhibited after an incubation time of 72 h, which suggests the efficient potential of BC900 towards naphthalene removal without hampering the native environment (J. B. Zhang et al., 2023).

Hamid *et al.*, in the same year, employed one-step and two-step synthesis methods to produce rice straw biochar (RSBC), chitosan-modified rice straw biochar (CT-BC), and thiol-grafted chitosan-modified biochar (TH@CT-BC) for the effective removal of cadmium (Cd) from contaminated water. These modifications aimed to enhance the adsorption capacity of the biochar by introducing thiol and chitosan functional groups. This resulted in an increase in nitrogen-containing functional groups and the C/N ratio on the biochar surface. However, a reduction in specific surface area was observed, likely due to partial pore infillment. Despite this, the modifications led to the development of a highly porous honeycomb structure, forming nanosheets that enhanced Cd adsorption. Among the synthesized materials, TH@CT-BC exhibited the highest adsorption capacity of 261.47 mg/g, followed by CT-BC with 103.14 mg/g, and RSBC with 29.64 mg/g, all at pH 5.5. The adsorption process was best described by the Langmuir isotherm model and followed pseudo-second-order kinetics. TH@CT-BC maintained its high efficacy in spiked river water, achieving 89 % Cd removal. The removal mechanism involved electrostatic interactions and surface complexation between TH@CT-BC and Cd^{2+} ions, confirmed through analytical techniques such as EDS, XPS, and FTIR. FTIR spectra revealed that the structural conformation of the biochar was preserved after Cd adsorption, with peak weakening attributed to the involvement of functional groups in complex formation (Fig. 10). (Hamid et al., 2023).



(A) Hydroxylation; (B) Ketone-enol tautomerism; (C) Decarbonization, ring opening andoxidation;
(D) Decarbonization andhydroxylation; (E) Further oxidation; (F) Oxidation;
(G) Oxidation and ring opening; (H) Hydrolysis and ketone-enol tautomerism.

Fig. 9. Mechanism involved for the removal of naphthalene using BC.

Similarly, Sakhiya et al. (2023) utilized rice straw biochar (RSBC) for the removal of manganese (Mn) and arsenic (As) from synthetic and natural field samples. RSBC was synthesized through pyrolysis at temperatures ranging from 400 °C to 600 °C. In a binary metal system, biochar produced at 600 °C (RSBC600) demonstrated higher adsorption capacities for As (4.51 mg/g) and Mn (3.61 mg/g), along with an increased surface area of 78.17 m^2/g. Using just 0.1 g of RSBC600, adsorption efficiency exceeded 85 %. The adsorption process was best described by Langmuir isotherms ($R^2 > 0.94$) and pseudo-second-order kinetics ($R^2 > 0.97$), offering insight into the interaction mechanisms between pollutants and RSBC. These interactions involved oxygenated functional groups on the biochar surface and metal ions through ion exchange, physical adsorption, electrostatic precipitation or co-precipitation, surface complexation, and cation-π interactions. During carbonization, carboxyl (-COOH) and hydroxyl (-OH) groups formed on the biochar surface, facilitating heavy metal complexation during adsorption. At lower pH (around 6), protons (H^+) were displaced from metal-binding sites, enhancing coulombic forces and electrostatic attraction, which increased the adsorption capacity for As and Mn ions, as follows:

$$\text{COOH} + \text{Metal ions (M)} + \text{water} \rightarrow \text{COO(M)} + H_3O^+ \tag{1}$$

$$\text{OH} + \text{Metal ions (M)} + \text{Water} \rightarrow \text{O(M)} + H_3O^+ \tag{2}$$

The adsorption efficacy of As ions was found to be much higher than that of manganese (Mn) ions, which can be attributed to As ions' smaller ionic radius and higher electronegativity. Oxygen, with an electronegativity of 3.44, exhibited a stronger attraction to electrons than the studied ions (As: 2.18, Mn: 1.55). Consequently, As ions were more strongly attracted to oxygen, a key component of BC functional groups such as -COOH, -C═O, and -OH, than Mn ions (Sakhiya et al., 2023).

Ahmed and colleagues explored the potential of rice straw BC modified with red mud to remove Pb(II) from wastewater. The modification increased the specific surface area of the BC, leading to enhanced Pb(II) removal efficiency at pH 5.0. The adsorption process adhered to pseudo-second-order kinetics and the Langmuir isotherm model. The Pb removal mechanism was attributed to the negatively charged groups on the BC surface, facilitating the conversion of Pb ions into Pb atoms.Moreover, the noncovalent interaction such as electrostatic interactions and H-bonding results in the enhanced removal of heavy metal ions (Ahmed et al., 2023).

Qu *et al.*, investigated the potential of RSB and titanium-modified RSB (Ti-RSB) in the removal and photocatalytic degradation of Ciprofloxacin (CIP). The maximum removal and degradation efficacy was 747.64 mg/g and 82.4–83.8 % at pH 5 and 7–9, respectively. The adsorption mechanism involves numerous interactive forces such as hydrogen bonding, π-π, and electrostatic. Remarkably, functional group (C–O) significantly influenced adsorption. TiO_2 modification leads to improved photocatalytic performance by altering the RSBC surface. Over a wide pH range (5−9), the resultant Ti-RSB composite showed better CIP removal effectiveness. The

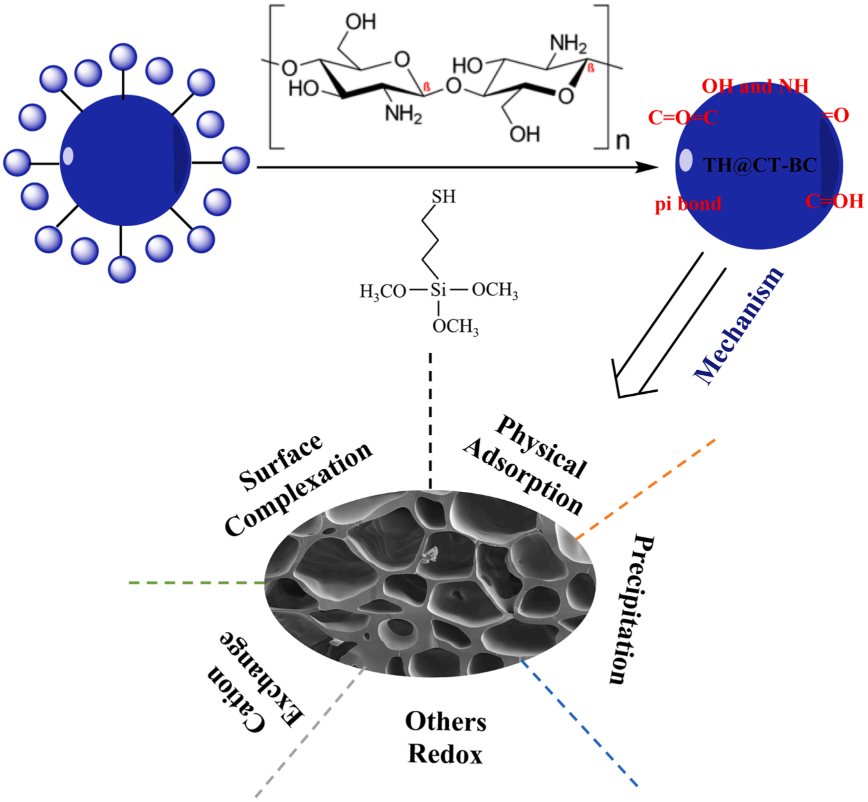


Fig. 10. Illustration of modification of BC and the mechanism associated for Cd adsorption.

degradation mechanism includes charge transfer, direct UV, and semiconductor charge separation. The degradation mechanism primarily involves the initial defluorination reaction followed by the breakdown of the piperazine ring. A key step in this process is the formation of a TiO_2 surface complex, resulting from the interaction of ciprofloxacin (CIP) with the titanium dioxide (TiO_2) surface. Electrons from the ligand-metal bonds in CIP are transferred to the conduction band of the biochar (BC) surface, which then interacts with electron acceptor molecules. The charge separation within rice straw biochar (RSB) creates active sites that facilitate the adsorption of CIP and TiO_2, leading to the generation of electron-hole pairs (e^--h^+) and dissolved O_2. The generated holes interacting with H_2O molecules lead to forming reactive species such as hydrocarbon and superoxide radicals ($^{\bullet}HOCl^-$, $^{\bullet}OH$ and $^{\bullet}Cl$). The generated radicals result in the piperazine ring opening of CIP, which further undergoes defluorination hydrolysis to form an intermediate. The intermediate was oxidized into inorganic components including CO_2, NH_3, H_2O, NO_3^-, NH_4^+, and F^- (Qu et al., 2023).

Liang *et al.* monitored the potential of $KMnO_4$ modified rice straw BC (MRSBC) for mitigating As(III) and Cd (II) in aqueous solutions. The maximum removal capacity was achieved in solutions containing both As(III) and Cd, reaching 141.1 mg/g for As and 224.4 mg/g for Cd at pH 7. However, the sorption capacities in individual solutions were lower, at 75.0 mg/g for As(III) and 122.1 mg/g for Cd. The Langmuir isotherm model best described the adsorption process and followed pseudo-second-order kinetics. The enhanced removal of As and Cd was attributed to the formation of type-A ternary complexes (MBC-Cd-As) and type-B ternary complexes (MBC-As-Cd). For Cd removal, the interaction was primarily driven by electrostatic adsorption between positively charged Cd ions and negatively charged functional groups on the BC surface, along with π-π interactions with the aromatic structures on MBC. In the case of As, the removal mechanism involved the oxidation of As(III) to As(V) by MnO_2, followed by sorption onto the MBC substrate (Fig. 11)(Liang et al., 2023).

In 2023, Wang *et al.* explored the use of rice straw BC to eliminate chlorophyll, malachite green, and imidacloprid (IMI). A BC-based composite (BBC) was effectively applied in practical scenarios, serving as sample pads in pesticide detection test strips and as a phytochrome purification agent within the QuEChERS method. The primary adsorption mechanisms were identified as π-π interactions and hydrogen bonding. The adsorption kinetics and isotherms were best described by the pseudo-second-order and Langmuir models, respectively. The BC demonstrated significant efficacy in removing chlorophyll from nine different solutions. After analysing 149 pesticides, BC proved to be a more efficient clean-up agent for phytochromes than graphitised carbon black. Notably, 123 out of the 149 pesticides showed acceptable recovery rates (Y. Wang et al., 2023).

In short, the employment of RSBC in water remediation offers a most efficient, and prominent approach to mitigating environmental contamination. Having plentiful functional groups and physicochemical properties of the BC, the adsorption process effectively removes a wide array of pollutants from water including heavy metals, organic compounds, and pharmaceuticals. Recent research indicates that modifying BC through physical, chemical, and biological treatments enhances its efficacy, significantly improving adsorption capacities and selectivity for specific contaminants. Notably, treatments such as potassium permanganate and titanium dioxide integration have augmented the surface area and porosity of BC, facilitating interactions such as π-π bonding, hydrogen bonding, and electrostatic interactions critical to remove pollutants like arsenic, cadmium, and ciprofloxacin.

The use of BC for water decontamination is further supported by its ability to reduce environmental toxicity. Research shows that modified BC has effectively broken-down toxic intermediates, thereby ensuring minimal disruption to microbial ecosystems. Despite these advancements, challenges such as refining the modification processes for diverse environmental conditions and implementing large-scale applications persist. Furthermore, while BC modifications enhance its efficacy, the associated costs and time requirements for these processes necessitate careful consideration to uphold economic feasibility. In summary, rice straw BC offers significant potential as an environmentally friendly, cost-effective solution for water remediation, aligning with global initiatives for sustainable

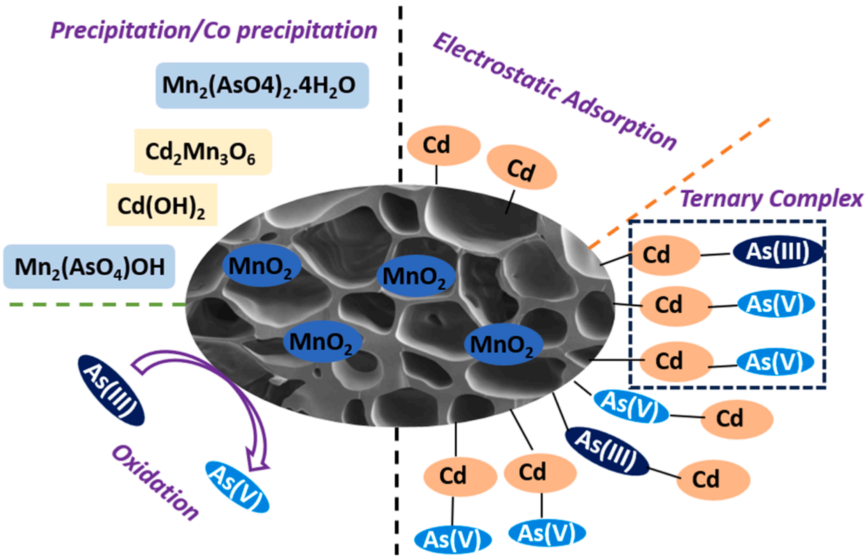


Fig. 11. Schematic illustration for the simultaneous removal of As and Cd using MBC.

environmental stewardship (Table 3).

4.2. Advanced oxidation processes (AOPs)

BC is widely employed to recalcitrate pollutants and antibiotics from wastewater, which only involves the transfer of contaminants from the aqueous phase to the adsorbents rather than eliminating them. In light of this, AOPs are considered efficacious methods for treating wastewater, specifically for removing organic pollutants. The catalytic activity of BC to eliminate pollutants is well-known and leads to the degradation, mineralisation and conversion of pollutants into less toxic components (M. Kumar et al., 2023; Nidheesh et al., 2021; Scaria et al., 2022; G. Wang et al., 2023). Consequently, it is imperative to examine the mechanism and process of

Table 3
Rice straw mediated BC and their modifications for the removal of different contaminants.

Modification	Contaminant	Removal capacity (mg/g)	Mechanism	Isotherm	Ref.
Unmodified	Sulfamethoxazole	9.2 mg/g	surface complexation; π-π electron interaction	Langmuir isotherm	(Ashebir et al., 2024)
TiO_2 modified	Ciprofloxacin	747.64	H-bond, π-π interaction, electrostatic interaction due to carbonyl	Langmuir isotherm	(Qu et al., 2023)
River coarse sand	Sulfamethoxazole and Trimethoprim	67.62 and 73.38	Electrostatic interactions	Langmuir isotherm	(L. Liu et al., 2022)
Unmodified	Sulfonamide	25.16	π-π interaction, H-bonding	Langmuir isotherm	(Fan et al., 2021)
Tannic acid	Tetracycline	308.00	π–π interaction, H-bonding, electrostatic interaction	Langmuir isotherm	(Chen et al., 2021)
Alkali/acid activated; Fe^{2+}/Fe^{3+} precipitated	Tetracycline	98.34	Pore-filling and H-bonding;	Langmuir isotherm	(Dai et al., 2020))
Magnetically modified	Safranin O dye	41.59	physical and chemical forces	Langmuir isotherm	(Phuong and Loc, 2022)
RSBC500	Cu (II)	29.8	-	Langmuir isotherm	(Kumar Sakhiya et al., 2020)
RSBC500	Methylene blue	51.34	Non-ionic lactone ring opening	Langmuir, Freundlich, and Redlich-Peterson adsorption isotherm	(Bhardwaj et al., 2022)
Fe–Mn oxide	Cd (II)	120.77	Coprecipitation, surface complexation, electrostatic attraction, and cation-π interaction	Langmuir isotherm	(Tan et al., 2022)
Albumin- and rice straw BC-alginate beads	PFAS	1.5 g L^{-1}	Hydrophobic sorption	Langmuir isotherm	(Militao et al., 2023)
La/Fe/Al oxides	Fluoride	111.11	Electrostatic attraction	Langmuir and Freundlich isotherm	(Zhou et al., 2022)
thiol-grafted composite of chitosan	Cd	261.47	Surface complexation and electrostatic attraction	Langmuir isotherm	(Hamid et al., 2023)
Red mud modified	Pb	426.84	Ion exchange and surface complexation.	Langmuir isotherm	(Ahmed et al., 2023)
RSBC500	Pb (II) and Zn (II)	7.93 and 25.73	Cation exchange due to electrostatic interaction and precipitation	Langmuir Isotherm	(Sakhiya et al., 2022)
Oxidized	U (VI)	242.65	Inner-sphere complexation	Langmuir isotherm	(Ahmed et al., 2021)
CH_3COOK activated	Zn (II)	255.88	-	Freundlich Isotherm	(Sakhiya et al., 2021)
Nanoporous	Hg (II)	209.65	Complexation	Langmuir isotherm	(Z. Liu et al., 2022)
immobilizing *Bacillus subtilis 168*	Zearalenone	93 %		Langmuir adsorption	(Han et al., 2023)
Iron-modified	Pb (II)	52.8	Electrostatic	Temkin's Freundlich, and Langmuir adsorption isotherm	(Ahmad et al., 2022)

contaminant degradation by RSBC in order to advance the usefulness of BC-based catalysts.

4.2.1. Radical-based oxidation

In recent years, AOPs have gained widespread use for the removal of refractory pollutants owing to their ability to generate various reactive radicals, such as hydroxyl radical ($^{\bullet}OH$), sulfate radicals ($SO_4^{\bullet -}$), carboxyl radical ($^{\bullet}COOH$), superoxide radical ($O_2^{\bullet -}$), and singlet oxygen ($^1O_2$) (Hassani et al., 2023; Scaria et al., 2021). A variety of activation techniques, including as ultrasound vibrations, heating, UV radiation, carbon-based materials, and transition metals, increase the potency of these radicals (Liu et al., 2023; Nidheesh et al., 2022; Wang et al., 2021a). In the case of carbon-based materials, BC can activate PMS, H_2O_2, PDS, and O_3, generating many reactive radicals due to oxygen-containing functional groups and persistent free radicals. This activation promotes the degradation of various organic pollutants, including dyes, pharmaceuticals, pesticides, and biomarkers (Gopinath et al., 2021; Nidheesh et al., 2021; Wang et al., 2019). For example, Zhu *et al.* demonstrated a catalytic system using ozone micro-nano-bubbles (O_3-MNBs) and NaOH-modified RSBC designed to remove 2,4-dichlorophenoxyacetic acid from water. The composite system achieved a removal rate of 89 %, attributed to the adsorption of O_3 onto the RSBC surface, which increased the adsorption energy between surface groups of RSBC and O_3 molecules. This interaction led to the dissociation of the O-O bond in O_3, resulting in the formation of $\bullet OH$ radicals that significantly contributed to the degradation of 2,4-dichlorophenoxyacetic acid (Zhu et al., 2022).

Additionally, the Fenton system is a highly effective and well-established AOP technology which involves the reaction of ferrous ion (Fe^{2+}) with H_2O_2 to generate reactive species (Wang et al., 2021b; Nidheesh, 2015). The dominant radical formed during the Fenton reaction is of $\bullet OH$ followed by other radicals (Eq. 1), and the generation of free radicals is affected by operating parameters such as temperature, pH of the solution, H_2O_2, and Fe^{2+} concentration. For instance, Wang *et al.* investigated the potential of ORSBC/H_2O_2 towards the degradation of oxytetraycline. The ORSBC/H_2O_2 system leads to 87.51 % degradation of oxytetracycline with a 251.07 mg/g quantity at 100 mg/L of drug. The degradation occurs owing to the generation of $\bullet OH$ and $O_2\bullet^-$(M. Wang et al., 2023). Similarly, Sang *et al.* reported $\bullet OH$, $O_2\bullet^-$, and $SO_4\bullet^-$ as the principal radicals responsible for the removal of ciprofloxacin during the presence of natural pyrite-modified RSBC and H_2O_2 (Sang et al., 2022).

Although the Fenton reaction possesses a high degrading capability for eliminating contamination parameters such as H_2O_2 instability, acidic environments, and metal leaching, it restricts the effectiveness of the Fenton system. It is also observed that the $SO_4\bullet^-$ exhibit superior oxidising capability and a higher redox potential as compared to $\bullet OH$, which provides prolonged selectivity and enhances degrading performance (Gujar et al., 2023; Scaria and Nidheesh, 2022). As a result, peroxymonosulfate (PMS) and persulfate (PDS)-based AOPs have become more well-known for their ability to remove pollutants by using the active sites in BC to generate radicals which initially involves the adsorption of PMS or PDS on BC.

In conclusion, radical-based oxidation processes particularly advanced oxidation processes (AOPs), have proven to be highly effective in the degradation of persistent pollutants during water treatment. These processes involve the generation of reactive radicals such as hydroxyl radicals ($\bullet OH$), sulfate radicals ($SO_4\bullet^-$), and superoxide radicals ($O_2\bullet^-$) through the activation of oxidants like PMS, PDS, and H_2O_2. The activation of BC further amplifies the efficiency of pollutant degradation by providing active sites for radical generation. Studies have showcased the effectiveness of modified BC composites in achieving substantial removal rates of pollutants such as 2,4-dichlorophenoxyacetic acid and oxytetracycline, with removal efficiencies reaching up to 89 % and 87.51 %, respectively.

However, the implementation of advanced oxidation processes (AOPs), particularly those based on Fenton chemistry, encounters various challenges such as the instability of hydrogen peroxide (H_2O_2), the necessity of acidic conditions, and the potential for metal leaching, all of which can restrict their effectiveness. The emergence of sulfate radical-based AOPs presents a promising alternative due to their superior oxidative capabilities and prolonged selectivity, thereby enhancing degradation performance. Despite these advancements, it is imperative to focus on optimizing reaction conditions and addressing potential side effects, such as metal leaching, which remain vital areas for further research. In summary, the amalgamation of radical-based oxidation processes with BC activation represents a potent and versatile approach for advanced water treatment, aligning with the escalating demand for sustainable and efficient environmental remediation technologies.

4.2.2. Non-radical pathway for contaminant removal

For contaminant removal, the activation of PMS and PDS using BC can proceed via both radical and non-radical pathways. Recently, non-radical pathways, especially those involving the activation of PMS/PDS through BC derived catalysts, have gained significant attention (Badiger and Nidheesh, 2023; Huang et al., 2022; Kohantorabi et al., 2021). Non-radical AOP pathways include electron transitions between pollutants and oxidants, singlet oxygen ($^1O_2$) production, and surface-confined reactions, thereby minimising the formation of oxidising radicals (Duan et al., 2018a). The non-radical pathway offers numerous merits like the complete utilisation of PMS/PDS oxidation potential, independence from solution pH, improved resistance to inorganic ion interference, and reduced formation of toxic radicals and by-products (Duan et al., 2018; Zhou et al., 2021). For instance, Yin *et al.* used experimental data and predictions from Density Functional Theory to investigate sulfamethoxazole breakdown utilising the non-radical $^1O_2$ oxidation route. Sulfamethoxazole's rate of degradation dramatically increased in the SBC/PDS system from 10.1 % in the PDS-only system to 94.6 %, mostly because of the non-radical route (Yin et al., 2019). Singlet oxygen ($^1O_2$) is the dominant non-radical oxidant due to its high reactivity potency towards electron-rich compounds (sulphides, amines, and phenols). $^1O_2$ can be generated through various mechanisms, including lattice oxygen evolution, $O_2\bullet^-$ generation, and PMS self-decomposition (Duan et al., 2018; Zhou et al., 2021). In another study, metolachlor degradation was significantly enhanced after 30 min of UV irradiation, with the elimination rate increasing from 0.0238 min^{-1} to 0.0357 min^{-1} when replacing the solvent with D_2O in the N-doped BC/PMS system (Ding et al., 2020).

In some cases, both radical and non-radical pathways coexist in BC-based AOP systems. For instance, Huang et al. observed a 99 %

degradation rate of tetracycline, attributed to the synergistic effect of •OH, $SO_4•^-$, and $^1O_2$ after PS activation by magnetic ORSBC (Huang et al., 2021). Likewise, Yang et al. reported the activation of H_2O_2 for oxytetracycline degradation by FeS-modified ORSBC, involving both radical ($SO_4•^-$, $O_2•^-$, and •OH) and non-radical (O_2 and oxygen vacancy) mechanisms (Yang et al., 2022). Since the radical vs non-radical route distinction is still up for discussion, it is difficult to pinpoint the crucial elements affecting these processes during antibiotic degradation on BC-based catalysts. Addressing this issue requires further in-depth research and analysis.

In summary, the examination of non-radical pathways for the elimination of contaminants in BC-based advanced oxidation processes (AOPs) offers a promising and innovative approach to water treatment. In contrast to conventional radical-based mechanisms, non-radical pathways, particularly those involving singlet oxygen ($^1O_2$) and direct electron transfer, present various advantages, including improved stability across diverse pH levels, decreased interference from inorganic ions, and reduced generation of harmful by-products. The significant enhancement in degradation rates demonstrated in studies such as the degradation of sulfamethoxazole (from 10.1 % to 94.6 %) signifies the effectiveness of these pathways when facilitated by BC-based catalysts. Furthermore, the increased degradation of metolachlor under UV irradiation and the coexistence of both radical and non-radical mechanisms in particular systems highlight the adaptability and efficiency of these methods.

However, the intricate nature of these processes especially the interaction between radical and non-radical pathways, poses a significant challenge in fully comprehending and enhancing these systems for practical use. The synergistic effects evident in BC-based systems, in which both pathways contribute to the breakdown of pollutants, indicate the necessity for more comprehensive research to determine the specific conditions and factors favouring one pathway over the other. As the field advances, a profound understanding of these mechanisms will be pivotal in devising more effective, selective, and environmentally sustainable water treatment technologies capable of addressing a broad spectrum of contaminants while minimizing secondary pollution. Hence, the choice of AOP for toxin or heavy metal removal is highly dependent on the nature of the pollutant and exhibit various advantages and disadvantages (Table 4). For organic toxins such as chlorpyrifos, atrazine, and malathion, photocatalysis, the Fenton process, and ozonation are preferred due to their ability to generate sufficient hydroxyl radicals to degrade these stable compounds. Electrochemical oxidation offers versatility in treating complex toxin mixtures, though its energy demands can be a limitation. For heavy metals like lead, mercury, arsenic, and cadmium, AOPs are more effective when used in conjunction with adsorption or precipitation processes, as they alter the metals' speciation to make them easier to remove.

4.3. *Soil amendment and agricultural benefits*

Rice straw biochar (RSBC) presents an impressive opportunity for use as a soil amendment, primarily due to its distinct physicochemical characteristics. One of its key features is its high porosity, which allows for effective air and water circulation within the soil. This porosity improves soil structure, promoting root development and overall plant health. Additionally, RSBC boasts a substantial surface area that facilitates the adsorption of nutrients and water, enhancing their availability to plants. The sorption properties of biochar also mean that it can help retain essential nutrients within the soil, reducing leaching and ensuring that crops have access to the nutrients they need over an extended period. Another notable aspect of RSBC is its mineral content, particularly the presence of beneficial minerals like silicon dioxide (SiO_2). Silicon plays a crucial role in plant health, contributing to improved resistance against pests and diseases, drought tolerance, and overall plant vigour. When incorporated into agricultural practices, RSBC can significantly improve water retention in soil, making it especially valuable in regions susceptible to drought and water scarcity. By enhancing moisture levels, RSBC aids in maintaining a healthy growing environment for crops (Li and Delvaux, 2019; Xiao et al., 2014).

Biochar is characterized by its unique porous structure and significantly high cation exchange capacity (CEC), which together facilitate the retention of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) within the soil matrix. This property enhances the bioavailability of these nutrients to plants, allowing for a gradual release that aligns more closely with plant uptake needs over time. Consequently, the use of biochar can substantially reduce the reliance on chemical fertilizers, thereby promoting sustainable agricultural practices and minimizing environmental impacts associated with fertilizer runoff and soil degradation

Table 4
Advantages and Disadvantages of AOPs for RSBC mediated water remediation.

AOP Method	Advantages	Disadvantages	Ref.
Photocatalysis	-High degradation efficiency for organic toxins - Low chemical input - Sustainable and environmentally friendly	- Requires UV/visible light source - Catalyst deactivation over time - Limited efficiency in turbid water	(Zambrano et al., 2022)
Radical-based Oxidation (e.g., Fenton, Ozone)	- Highly reactive hydroxyl radicals (•OH) degrade a wide range of pollutants - Fast reaction rates	- Requires pH control (Fenton) - Sludge generation (Fenton) - High operational costs (ozone)	(Khan et al., 2023)
Non-radical-based Oxidation (e.g., persulfate, permanganate)	- Can operate in a wider pH range - Effective for specific pollutants - Lower risk of sludge generation	- Slower reaction kinetics compared to radical-based methods - Requires chemical activators or catalysts	(Dong et al., 2021)
Electrochemical Oxidation	- Highly controllable process - Effective for complex toxin mixtures and recalcitrant compounds - No need for chemical additives	High energy consumption - Electrode fouling - Costly electrode materials	(Najafinejad et al., 2023)

(Wang et al., 2018). Moreover, research has indicated that biochar can effectively ameliorate soil pH, particularly in acidic soils, leading to an improved plant-growing environment. By increasing soil pH, biochar enhances nutrient availability and fosters beneficial microbial activity, which is vital for soil health and fertility. This dual effect of nutrient retention and pH adjustment makes biochar a valuable amendment for enhancing soil quality and promoting sustainable farming systems.

One of the notable advantages of using RSBC as a soil amendment is its rich silicon (Si) content, which adds significant agronomic value to agricultural practices. Silicon plays a crucial role in enhancing plant health by increasing their resistance to various stressors, including herbivorous pests, pathogenic diseases, and water scarcity due to drought. When RSBC is integrated into the soil, it serves as a slow-release silicon source, gradually supplying this essential element to plants over time. This gradual release promotes enhanced plant resilience and has the potential to improve crop yields significantly (Li and Delvaux, 2019). In addition to its silicon content, the incorporation of biochar is associated with long-term carbon sequestration in soils. Biochar has a unique structural composition that renders it highly stable and resistant to microbial decomposition, allowing it to persist in the soil for extended periods. This stability is critical for climate change mitigation, as it helps sequester carbon, effectively storing it in the soil and thereby reducing the levels of atmospheric CO_2. Consequently, the application of RSBC not only enhances soil fertility and plant growth but also contributes to sustainable agricultural practices and environmental stewardship (Xiao et al., 2014).

In conclusion, the dual functionality of RSBC as both a soil amendment and a water remediation agent illustrates its versatility and effectiveness in environmental remediation efforts. These synergistic benefits emphasize the potential of RSBC to enhance sustainable agricultural practices, bolster climate resilience, and promote improved soil health.

5. Factors affecting the adsorption efficiency

5.1. Operational parameters

The adsorption efficiency of biochar (BC) typically decreases with increasing temperature (Li et al., 2020), a trend that may result from interactions between BC and organic matter (Shemawar et al., 2021). For instance, Yin *et al.* studied the effect of a humic acid coating on rice straw BC composites in the adsorption of pentachlorophenol. The presence of humic acid was found to reduce adsorption capacity by blocking the BC's micropores, thereby diminishing its surface activity(Yin et al., 2021). Similarly, Zhang *et al.* observed a decline in BC's adsorption efficiency over time, primarily due to the accumulation of organic matter on the BC surface (Zhang et al., 2020).

Wu et al. (2022) investigated the combined effects of time and temperature on the adsorption behavior of cadmium (Cd (II)) using lignin-derived BC composites. Lignin was carbonized at various temperatures, and the adsorption performance towards Cd (II) was assessed. The study revealed that increasing pyrolysis temperature led to the decomposition of functional mineral groups on the BC surface. However, Cd (II) adsorption efficiency improved with higher carbonization temperatures, increasing from 573.27 mg/g at 200°C to 635.44 mg/g at 500°C. Initially, adsorption was rapid due to the availability of electron-donating groups, providing more adsorption sites. Equilibrium was reached within 30 minutes, with adsorption kinetics following a pseudo-second-order model (Wu et al., 2022).

Additionally, the impact of pH on BC's adsorption performance has been well-documented, as both surface charge and pH significantly affect adsorption capacity (Xiang et al., 2019). Cation adsorption is enhanced at pH levels below 6.02, whereas anion adsorption is more favorable at pH levels above 8.15. The pH at the zero-point charge plays a key role in determining the effectiveness of active surface sites of BC (Gautam et al., 2021). The negative zeta potential of BC improves its ability to adsorb positively charged contaminants (Tan et al., 2020). Furthermore, higher pyrolysis temperatures generally reduce the zeta potential of BC, leading to a decrease in adsorption yield. BC produced at lower pyrolysis temperatures may be more effective due to the higher negative surface charge (Yaashikaa et al., 2020).

The interaction between BC and agrochemicals also plays a crucial role in reducing the bioavailability of harmful substances in soil and water. For example, Liu et al. (2018) and Li et al. (2018) examined the effectiveness of different BC types in lowering the bioavailability of insecticides such as chlorpyrifos and carbofuran to spring onions. Their findings demonstrate BC's potential in mitigating agrochemical contamination, underscoring its utility in environmental remediation (Issaka et al., 2022).

5.2. Surface properties and functional groups

Apart from the operational parameters, the properties of BC are very critical in affecting the mitigation of contaminants. The porous nature of BC is fundamental in determining its adsorption efficiency. BCs with a well-developed microporous structure (pores < 2 nm) are particularly adept at adsorbing small ions, such as heavy metals, due to their high specific surface area, which provides abundant adsorption sites. Meanwhile, BCs with mesoporous structures (pores 2–50 nm) are better suited to adsorb of larger organic pollutants.

The pyrolysis temperature and biomass source directly influence the development of these pore structures. For instance, BC produced at moderate pyrolysis temperatures (300–600°C) typically exhibits a balance between micro- and mesopores, making it versatile for different pollutants. Higher pyrolysis temperatures (>700 °C) generally increase micropore formation, which enhances heavy metal uptake but may reduce efficiency for larger organic molecules. Furthermore, the surface chemistry of BC, particularly its functional groups, plays a key role in pollutant removal. BC surfaces typically contain functional groups such as -OH, -COOH, and -C=O, which facilitate pollutant binding *via* ion exchange and electrostatic attraction. For example, BC with abundant oxygen-containing groups is highly effective at capturing positively charged heavy metals like lead (Pb^{2+}) through ion exchange mechanisms.

The aromatic structure of BC also allows for π-π interactions with organic contaminants, such as pesticides, further boosting its adsorption potential. Surface functionalization can be tailored through chemical treatments, enabling BC to target specific pollutants with greater precision(Zeghioud et al., 2022).

5.3. Modification parameters

Various modification techniques can enhance its adsorption performance. Chemical treatments, such as acid (e.g., H_3PO_4, HNO_3) or alkaline (e.g., KOH) treatments, modify the surface characteristics, making BC more effective for specific pollutants. Acid-treated BC exhibit improved heavy metal adsorption, while base-treated BCs tend to enhance organic pollutant removal. Additionally, BC can be functionalized by incorporating NPs like metal oxides (e.g., Fe_3O_4 or TiO_2). These hybrid materials not only increase adsorption capacity but also add new functionalities, such as magnetism, which facilitate easier recovery of BC after water treatment. Such modifications have proven highly effective in tackling complex contaminants, including pharmaceuticals and industrial chemicals(Murtaza et al., 2024).

5.4. Isotherm models

Various models, including the Langmuir, Freundlich, Temkin, and BET (Brunauer-Emmett-Teller) adsorption models, have been applied to describe the adsorption process on biochar (BC). Among these, the Langmuir and Freundlich models are the most commonly used. The adsorption behavior of metal ions on both unmodified and modified rice-based BCs varies depending on the modification type and the composition of the metal ion solution. Despite being derived from the same rice-based source, different sorption models may be more suitable based on specific conditions. For example, Pb(II) adsorption on unmodified rice straw BC in a single-metal system follows the pseudo-second-order kinetic model and is best described by the Langmuir isotherm. In contrast, Pb(II) adsorption on hydroxyapatite-modified rice straw BC in the same system adheres to the pseudo-second-order kinetic model but follows the Freundlich isotherm. Interestingly, when Pb(II) is adsorbed in a ternary solution containing Pb(II), Cu(II), and Zn(II), the hydroxyapatite-modified BC aligns with the pseudo-second-order kinetic model and the Langmuir isotherm.

Similarly, the adsorption of Cu(II) and Zn(II) on both unmodified and hydroxyapatite-modified rice straw BC is influenced by the specific composition of the metal ion solution. For instance, As(III) and Cd(II) adsorption on $KMnO_4$-modified rice straw BC in a binary solution follows the pseudo-second-order kinetic model and the Langmuir isotherm. Comparable trends have been observed for single-metal adsorption on raw rice straw BC and rice husk. However, studies on adsorption in mixed metal ion and organic compound solutions remain limited for both unmodified and modified BCs, making direct experimental comparisons challenging(Liu et al., 2024).

6. Bibliometric analysis

To analyse the research conducted in the field of rice straw derived BC for water decontamination, bibliometric analysis was conducted in which Scopus database was searched with keywords “Rice Straw”, “BC”, “Water Remediation”, “Adsorption”, “Advanced Oxidation Procsess”. Moreover, for the more scientific sound research, filter were applied including the exclusion of conference papers, review articles and book chapters as these kinds of articles don’t exhibit any novelty as the data might be already reported in research articles. The search only contains research articles varies from 2018 to 2024 (accessed on 22.10. 2024). Further, VoS Viewer was utilised to generate the work cloud based on the cooccurrence of keywords as the academic papers prefer keywords for the classification of their core research. To generate the work cloud, a threshold of minimum five times was applied. The finding suggests that the primary way to remove the pollutants from water using BC is adsorption. The analysis contains four clusters which commonly focus on

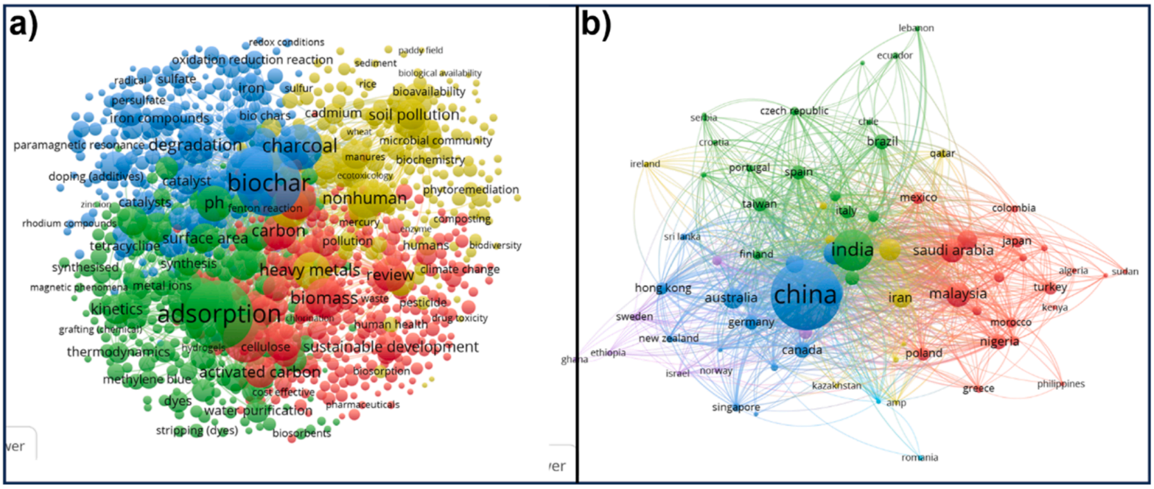


Fig. 12. Word cloud based on the keywords co-occurrence (a) and country wise (b) (VoS Viewer).

the i) BC efficiency for the removal of organic contaminants, thermodynamic and kinetic models as well as properties of BC (green); ii) Modified characteristics of BC towards the removal of heavy metal (blue); iii) role of BC towards the attainment of sustainable development goals and their adaventageous part over other activated carbon based materials (red); and iv) alternative of reuse of rice straw based biomass in field application for sustainable environment (yellow) (Fig. 12a).

Additionally, the analysis was performed country wise which suggests that the maximum research has been done in China followed by India, Canada, Germany, Hongkong and Australia (Fig. 12b)

7. Challenge and future perspectives

Although BC demonstrates remarkable efficacy in removing emerging water contaminants including organic and inorganic *via* adsorption and AOPs, it may impose several environmental challenges. For instance, various kinds of lethal components, such as polycyclic aromatic hydrocarbons (PAHs), leachable inorganics, and metal cyanide, present in BC are hazardous to humanity as well as environment. Additionally, the surface functional groups or characteristics of BC change due to the irreversible interactions between intermediates and adsorbed contaminants, which hinder catalytic active sites and surface adsorption, resulting in decreased removal efficiency and stability. Hence, these issues must be fully addressed highlighting the necessity of logical BC-based material design. Moreover, concentrations of pollutants in water such as surface water and groundwater are often low. Nevertheless, BC effectively treated these contaminants even at very low concentrations. However, the toxicity of the intermediate pollutants that AOPs produce must be considered. Hence, for a thorough grasp of the water treatment process, it is also necessary to properly assess the effects of coexisting compounds in the water. Moreover, all facilities, including palm oil mills, rubber factories, and various food manufacturing industries, are required to comply with the Environmental Quality Regulation 1979 concerning licensing, waste disposal, and control measures for water and air quality. The regulatory framework governing agricultural waste management is rooted in the Environmental Quality Act 1974, along with specific subsidiary regulations. The management of rice straw, a significant agricultural byproduct, is governed by local environmental regulations aimed at minimizing open burning and promoting sustainable practices such as composting and biomass utilization. Additionally, the Renewable Energy Act 2011, supported by the Sustainable Energy Development Authority (SEDA), encourages the utilization of rice straw for renewable energy generation through incentives like Feed-in Tariffs and tax exemptions, aligning with national objectives for expanding the biomass industry and reducing environmental impacts (Singh and Brar, 2021).

Most existing research on using BC to remove pollutants from water generally focuses on specific contaminants whereas various kinds of pollutants coexist in water. It is therefore essential to conduct a detailed investigation into the effectiveness and mechanisms of BC-based materials in eliminating different contaminants from actual wastewater. Practical applications also highly prioritise tackling the problem of effectively recycling and regenerating BC-based products. Furthermore, a more profound investigation into the mechanisms underlying the degradation of antibiotics and other organic/inorganic water contaminants through SBC-based materials is essential. The dominant role of specific mechanisms and their respective contributions still need to be determined. Resolving these uncertainties is crucial for enhancing the pollutant removal capabilities of SBC and facilitating its prospective industrial application.

Furthermore, it is crucial to evaluate the potential environmental risks imposed by the practical use of RSBC-based adsorbents and catalysts. Factors such as their transport, transformation, possible toxicity, and the economic feasibility of the overall process must be considered. Future research should include a life cycle assessment of RSBC in wastewater treatment to assess their environmental impact thoroughly. The subject of managing rice straw and utilizing BC aligns directly with various United Nations Sustainable Development Goals (UNSDG), particularly Goal 6 (Clean Water and Sanitation), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action). This research contributes to reducing water pollution, improving resource efficiency, and mitigating climate change impacts by advocating for the sustainable use of agricultural waste for environmental remediation. Engaging in critical discussions is essential to ensure that BC production and application do not introduce new ecological hazards. A comprehensive life cycle assessment and the development of supportive policy frameworks are crucial to advancing sustainable practices. In this regard, SWOT analysis has been performed which signifies the strengths, weakness, opportunities and threats associated with the BC application (Fig. 13).

8. Conclusions

Rice straw biochar (RSBC) stands as a promising solution for sustainable waste management, offering significant benefits for environmental remediation and resource recovery. Its remarkable capacity to adsorb up to 95 % of heavy metals and organic pollutants from wastewater not only mitigates environmental risks but also adds economic value by transforming agricultural waste into a useful product. This dual benefit supports global goals of sustainability and economic efficiency. However, despite these promising attributes, several challenges limit the widespread application of RSBC. One critical challenge is the optimization of RSBC for large-scale applications. The production processes, while effective on a smaller scale, require further refinement to ensure consistency, cost-effectiveness, and enhanced stability across diverse environmental conditions. Additionally, concerns regarding the potential toxicity of BC and its long-term environmental impact must be addressed, particularly when used in large quantities or under varying climatic conditions. The need for more comprehensive toxicological assessments and lifecycle analyses to completely evaluate the sustainability of BC applications is one of the most prominent research gaps in this aspect.

In terms of future research, efforts should focus on enhancing the regeneration capacity of BC to increase its reusability, thereby improving cost efficiency and reducing waste. Moreover, integrating RSBC into existing waste management and energy production systems offers a valuable opportunity to reduce methane emissions and contribute to global carbon reduction efforts, supporting

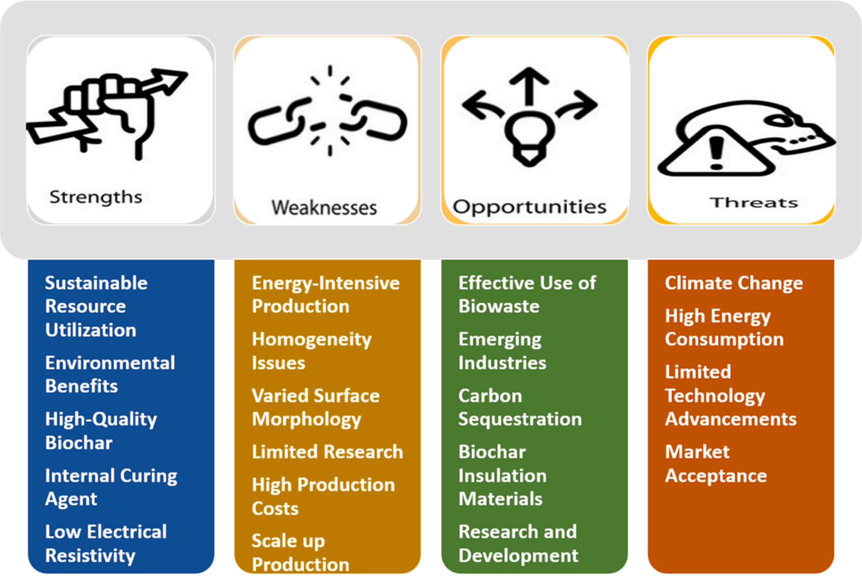


Fig. 13. SWOT Analysis for the employment of RSBC for water remediation.

international climate action initiatives. To realize these goals, interdisciplinary collaboration across fields such as material science, environmental engineering, and policy development is essential. While RSBC aligns with the United Nations Sustainable Development Goals (UNSDGs), particularly in promoting clean water, responsible consumption, and climate action, further innovation is necessary to maximize its potential. Future research should explore advanced BC modification techniques to enhance its adsorption efficiency and stability, investigate scalability strategies, and assess the environmental and health impacts more thoroughly. By addressing these gaps, RSBC can evolve from a promising material to a cornerstone of sustainable environmental management and a critical tool in the fight against global environmental challenges.

CRediT authorship contribution statement

Jagpreet Singh: Writing – original draft, Methodology, Writing – review & editing, Visualization, Validation, Software, Validation, Data curation. **Monika Bhattu:** Writing – review & editing, Visualization, Validation, Software, Formal analysis, Data curation. **Rock Keey Liew:** Writing – review & editing, Formal analysis. **Meenakshi Verma:** Writing – review & editing, Investigation, Formal analysis. **Satinder Kaur Brar:** Writing – review & editing, Supervision, Project administration, Formal analysis, Conceptualization. **Mikhael Bechelany:** Writing – review & editing, Project administration, Formal analysis. **Rajendrasinh Jadeja:** Supervision, Project administration, Formal analysis, Conceptualization.

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.

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Data availability

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

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