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Biochar

REVIEW **Open Access**

Innovative applications of biochar in nuclear remediation and catalysis

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Abstract

Emphasizing its potential for environmental sustainability, this review investigated how biochar—a carbon-rich material obtained from biomass pyrolysis—might be used into nuclear science and technology. High surface area, porosity, and functional groups give biochar special adsorption capacity, which qualifies it as a potential instrument for radiation cleanup and improving energy economy in nuclear uses. From the historical development of nuclear physics to the creative application of biochar in nuclear waste management and radiation shielding as well as its contribution to sustainable nuclear energy, the study covers several spheres. Biochar presents amazing efficiency in adsorbing and immobilizing radionuclides in the field of nuclear waste management, therefore establishing itself as a viable substitute for more traditional approaches. Its uses cover handling of high-level radioactive materials as well as treating low-level radioactive effluents. The paper also looks at using biochar as radiation shielding since its carbonaceous character produces strong, light-weight protective barriers. Using controlled pyrolysis and later changes, the paper addresses advanced manufacturing processes for customizing nuclear-grade biochar for particular uses. Within the nuclear industry, economic studies emphasize the affordability and possible financial gains of biochar, as well as its market potential and commercialization techniques. Lifetime analysis helps to evaluate environmental effects and sustainability by stressing the part of biochar in carbon sequestration and lowering of ecological footprints. The paper discusses safety and regulatory issues, how artificial intelligence and machine learning might be used for material optimization, and the limits and difficulties in using biochar. Practical case studies highlight its success in nuclear environments. The study ends by placing biochar as a major component in creating sustainable nuclear technology, which calls for continuous research, cooperation, and creativity.

Highlights

- The adsorption capability of biochar makes it a sustainable tool for radiation cleanup and energy efficiency in nuclear tech.
- It offers a cost-effective, lightweight solution for nuclear waste management and radiation protection.
- The study underscores the potential of biochar in carbon sequestration and sustainability in the nuclear industry.

Keywords Biochar, Nuclear waste management, Radiation shielding, Environmental sustainability, Radioactive contaminant adsorption

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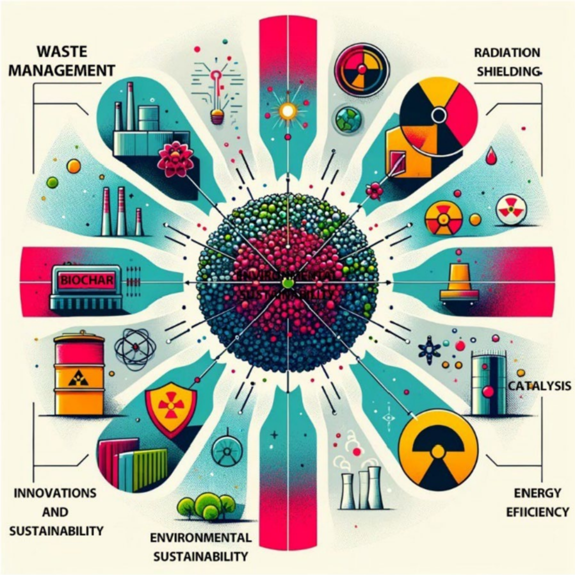
Graphical Abstract



1 Introduction

Modern society depends much on nuclear science and technology since they provide answers for scientific developments, medical treatments, and energy generation (Andrews et al. 2022). But the usage and handling of nuclear materials provide major difficulties, especially with relation to radioactive waste and how it affects the environment and human health (Deng et al. 2020a). Protecting populations and ecosystems from the negative consequences of radiation exposure depends on the remediation of nuclear waste. Good nuclear waste management guarantees the safe running of nuclear plants, lowers the risk of radiation-induced diseases, and helps to avoid environmental pollution (Natarajan et al. 2020). Remedial actions protect biodiversity, preserve ecosystem services, and help to conserve the natural resources by immobilizing radionuclides and stopping their migration into ecosystems (Tran 2024). Moreover, tackling nuclear waste helps to boost public confidence in nuclear technologies and promotes the ongoing use of nuclear energy as a low-carbon source to satisfy world energy consumption (Halkos and Zisiadou 2023).

Because of its unusual qualities, biochar—a carbon-rich material created by pyrolyzing organic biomass in low-oxygen environments—has attracted a lot of interest (Nuraini et al. 2022). Its great surface area, porosity, and richness of functional groups help to explain its remarkable adsorption capacity, therefore rendering it a flexible material for environmental cleanup (Amalina et al. 2023). Usually burning biomass materials, such as wood, agricultural waste, or manure, at temperatures ranging from 300 to 700 °C (Seow et al. 2022)—the biochar synthesis process, is involved. Atinafu et al. (2023) claim that by changing the physical and chemical structure and thus boosting the carbon content, thermal breakdown improves the stability and lifetime of the material. The resulting biochar, according to Rahman et al. (2020), can remain stable in the environment for hundreds of years, therefore helping to sequester carbon and improves soil.

An area of developing interest in nuclear science and technology is the possibilities of biochar (Bates 2010). Its great capacity to adsorb and immobilize a broad spectrum of radionuclides offers a novel method of managing nuclear waste and reducing environmental contamination (Jang et al. 2018). Regarding disposal and environmental effect, radioactive waste from nuclear power plants presents major difficulties (Nuttall 2022). Many times, traditional nuclear waste management techniques are complicated and expensive (Rahman et al. 2011; Suh et al. 2020). Because of its availability, low cost, and extraordinary adsorption properties (Shen et al. 2020), biochar turns out as a sustainable substitute. Its uses in solid waste (Li et al. 2024) immobilize high-level radioactive elements and cure low-level radioactive wastewater. The tunable character of biochar lets its features be changed to fit certain needs, so it is adapted to solve different problems related with nuclear waste (Foster 2023).

For radioactive waste, for example, the affinity of biochar for some radionuclides could be changed to increase its efficacy (Datta et al. 2022). Moreover, biochar has several other nuclear-related applications beyond waste management. Its carbonaceous make-up suggests potential as a radiation-shielding material (Zhang et al. 2022b; Li et al. 2024). This is good for the development of portable, effective radiation barriers—a necessary part of nuclear plant security protocols. Including biochar into nuclear site rehabilitation could help to lower soil and water pollution, therefore safeguarding ecosystems and public health particularly in areas affected by nuclear accidents or leaks (Murtaza et al. 2023).

Although biochar is increasingly used in nuclear remediation and catalysis, some research gaps still exist and demand more study even with these developments in its application (Wang and Wang 2019). Most studies have concentrated on short-term laboratory experiments, thus providing limited information on how structural integrity and adsorption capacity of biochar are affected under prolonged exposure to radiation and harsh conditions typical of nuclear waste storageas well as long-term stability of biochar in nuclear environments is not well understood (Qiu et al. 2022). Determining the feasibility of biochar in nuclear waste management depends on an awareness of these long-term interactions (Ahmad et al. 2014). While changes such as doping with metals or functionalization with nitrogen or oxygen groups have been investigated to improve catalytic performance, there is a need to identify the most effective modification strategies that enhance the selectivity, capacity, and reusability of biochar in adsorbing radionuclides (Huang et al. 2024). Optimization of biochar modifications for enhanced catalytic activity requires systematic research. Moreover, there is a dearth of pilot-scale or field studies showing the efficacy, feasibility, and financial viability of biochar in actual nuclear remediation projects; most research to date has been conducted at the laboratory scale under simulated conditions that may not fully represent real-world scenarios (Mohan et al. 2014). Addressing pragmatic problems and validating laboratory results in operational settings depend on scaling up (Kookana et al. 2011). While adsorption is acknowledged as a fundamental process, the specific roles of functional groups, mineral components, and pore structure in binding different radionuclides need clarity; the mechanistic knowledge of radionuclide interactions with biochar also requires additional elucidation (Da et al. 2022). A better mechanistic knowledge might help to build biochar materials meant for specific radionuclide elimination. Furthermore, thorough evaluations of the environmental impact and safety are limited, including possible hazards related to the use of biochar in nuclear environments; hence, regulatory compliance and public acceptance depend on an evaluation of the safety, possible for secondary contamination, and life-cycle impacts of biochar applications (Chen et al. 2021).

This review sought to synthesize current knowledge by means of a thorough overview of the uses of biochar in nuclear remediation and catalysis, highlighting important results from recent studies, summarizing the properties of biochar materials pertinent to these uses, so addressing these gaps. Analyzing approaches employed, the efficacy of various biochar kinds and alterations, and issues faced in past studies, it critically examined current research to find strengths, limits, and contradictions. Future research directions are also suggested here: long-term stability assessments of biochar in nuclear environments, development of standardized methods for biochar production and modification suited to nuclear applications, initiation of pilot-scale and field studies to evaluate practical feasibility and effectiveness, enhancement of mechanistic studies to better understand radionuclide-biochar interactions, and assessment of environmental impacts while establishing safety protocols.

1.1 Novelty and significance of this review

Biochar has been widely studied in environmental science and agriculture, with reviews often focusing on soil amendment, carbon sequestration, or water remediation. However, investigations into the role of biochar in nuclear science and technology—including its applications in nuclear waste management, radiation shielding, and catalysis—are comparatively recent. To underscore the novelty and importance of the present review, this section provides:

1. A visualization of the increasing academic attention given to biochar-related nuclear research by showing publication and citation trends.
2. A comparative table summarizing existing published reviews in related areas and illustrating how this paper addresses critical gaps and proposes new directions.

1.1.1 Publication trends in biochar-nuclear research

As illustrated in Fig. 1, publications combining the terms "biochar" and "nuclear" (or "radioactive," "radiation," etc.) have shown exponential growth over the past decade. While the overall number of articles is still modest compared to general biochar research, this accelerating trend

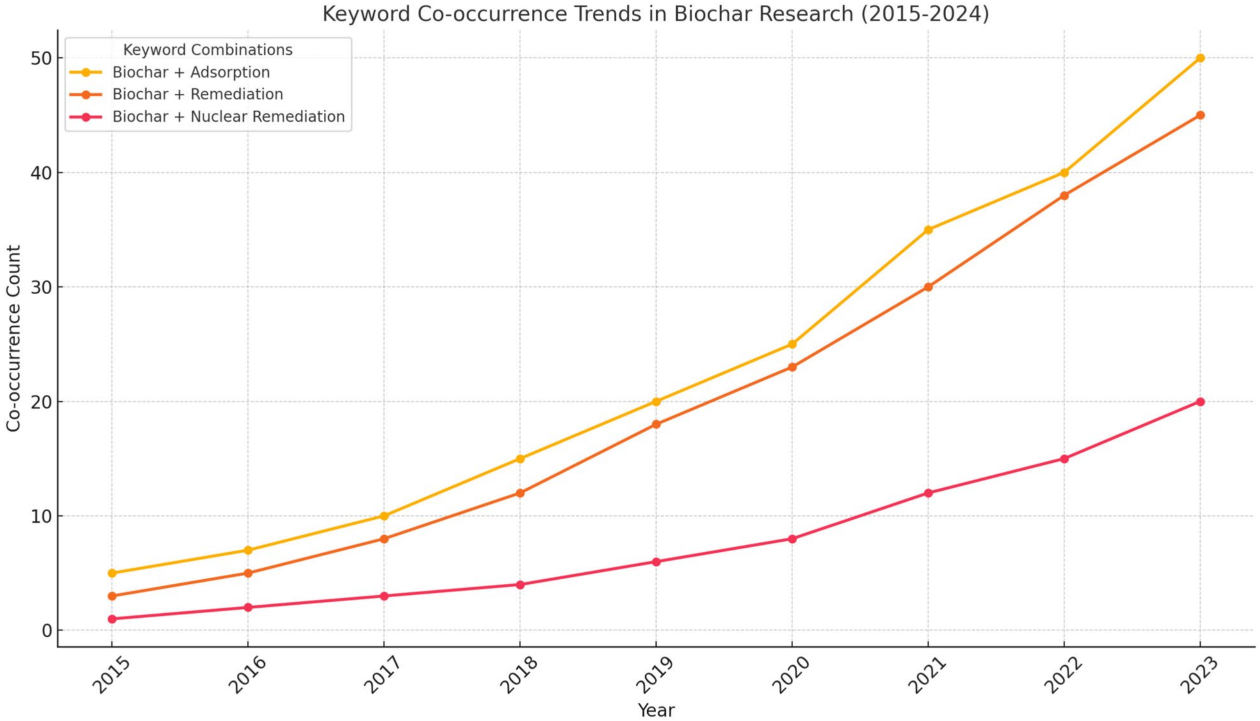


Fig. 1 Trends in keyword co-occurrence in biochar research (2015–2023) (Yang et al. 2023; Wu et al. 2023; Li et al. 2020a; Kumar et al. 2023). This figure illustrates the number of publications mentioning both "biochar" and "nuclear" (or "radioactive," "radiation," etc.) in their titles, abstracts, or keywords, based on searches of major academic databases (Scopus/Web of Science) from 2014 to 2023. Citation counts for these papers likewise exhibit an upward trend, reflecting increased research interest and perceived importance of the topic

indicates growing recognition of the potential of biochar for advancing nuclear science and technology.

1.1.2 Comparison with existing reviews

Although a few reviews have touched on aspects of biochar for radionuclide adsorption or environmental remediation, a comprehensive analysis of biochar in the nuclear sector—spanning waste management, radiation shielding, catalysis, and economic/environmental assessments—remains scarce. Table 1 compares key published reviews relevant to biochar and nuclear/environmental applications, highlighting how the present study differentiates itself.

This review offers several distinctive advantages. It takes a holistic approach by covering radioactive waste management, radiation shielding, catalysis, lifecycle assessments, economics, and ML approaches—an integration rarely found in the literature. Through case studies on uranium, cesium, strontium, and technetium, the review underscores practical examples while addressing regulatory and safety protocols, ensuring that laboratory findings align with nuclear-industry standards. In machine-learning-enhanced material optimization, it moves beyond conventional trial-and-error methods, showing how predictive analytics guides biochar design and scale-up. Looking ahead, future outlooks and sustainability are emphasized by discussing carbon sequestration and circular economy considerations, situating nuclear applications of biochar within broader environmental goals. Overall, this work provides a comprehensive nuclear emphasis, delving into nuclear-specific challenges like radionuclide immobilization and harsh thermal conditions. It adopts an innovation-driven perspective by focusing on advanced production methods, catalytic roles, and pilot-scale data to map a clear path for accelerating biochar use. Lastly, it promotes a sustainability and policy interface, highlighting economic feasibility, regulatory compliance, carbon neutrality, and public perception—essential factors for transitioning from research to real-world deployment.

2 Historical context of nuclear science and technology

2.1 Evolution of nuclear technologies

Since the discovery of radioactivity by Henri Becquerel in 1896 and the pioneering work of Marie and Pierre Curie in isolating radioactive materials like radium and polonium (Turrell 2021; Draganic and Adloff 2020) (Fig. 2), nuclear science and technology have drastically changed. Key events in the use of nuclear energy were

Table 1 Comparative overview of key biochar review articles and their relevance to nuclear applications

References	Scope	Coverage of nuclear aspects	Novel contributions	Limitations	Comparison with current review
Mohan et al. (2014)	Biochar in water remediation	Mentions heavy metals, limited radionuclide adsorption	Early overview of biochar adsorbents for contaminants	Does not address radiation shielding or nuclear catalyst applications	The present review extends the scope beyond adsorption of heavy metals to include waste management of high-level radionuclides, radiation shielding, and catalytic roles in nuclear processes
Ahmad et al. (2014)	Sorption for contaminant management	Includes trace discussion on radioactive elements	Provides fundamental adsorption mechanisms	Lacks detailed case studies in nuclear contexts	We present in-depth nuclear case studies (e.g., uranium, cesium, strontium removal) and analyze long-term stability under radiation and thermal stress
Wang and Wang (2019)	Biochar for general environmental cleanup	No dedicated nuclear section	Comprehensive discussion of biochar surface chemistry	Primarily addresses wastewater & soil, no nuclear scenario	We bridge nuclear technology by discussing radioactive wastewater and nuclear operational environments, plus ML-based optimization for targeted radionuclide adsorption
Guo et al. (2023a, b)	Lignin-derived and modified biochar for uranium removal	Focused primarily on U(VI) capture from nuclear wastewater	Demonstrates advanced biochar modifications with high adsorption capacity	Limited coverage of other radionuclides (Cs, Sr) or radiation shielding	Our review broadens the scope to multiple radionuclides, includes radiation-shielding approaches, and examines economic & regulatory aspects for full nuclear sector integration
Present review	Biochar's multi-faceted role in nuclear tech	Adsorption, shielding, reactor efficiency, catalysis, ML-driven design	Spans historical perspective, advanced production, safety standards, economics, and ML for materials optimization	–	Synthesizes cross-disciplinary data, addresses long-term performance under nuclear conditions, and proposes a research agenda for scaling, regulation, and public acceptance

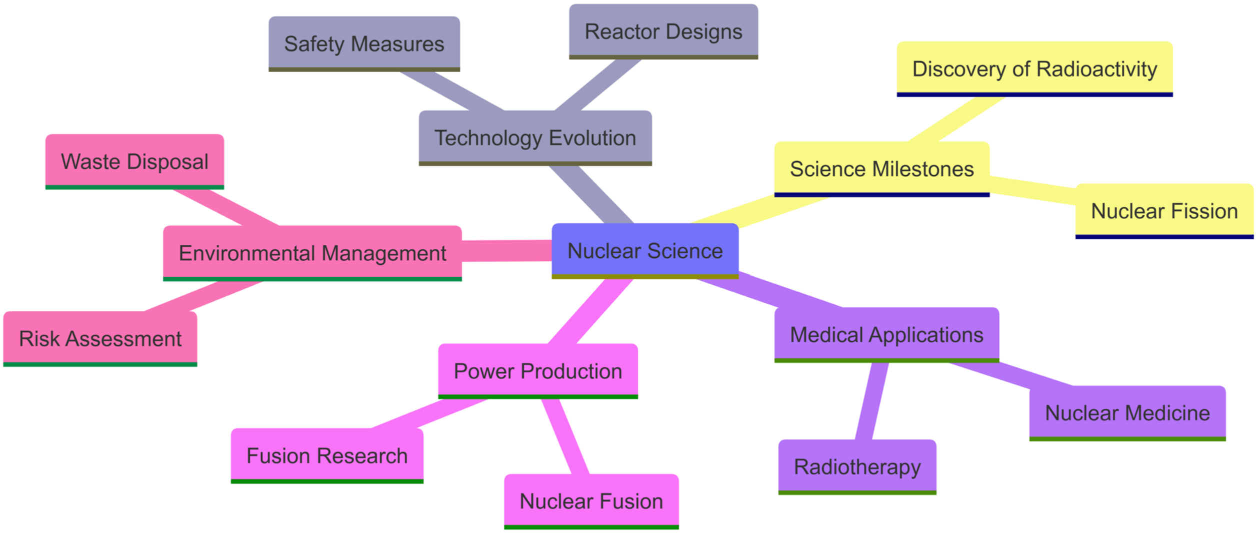


Fig. 2 Advancing science and industry: the multifaceted application of nuclear technology (Mekonen 2023; Udalova 2020)

the discovery of nuclear fission by Otto Hahn and Fritz Strassmann in 1938 and the construction of the first nuclear reactor by Enrico Fermi in 1942 (Eidemüller 2021; Esposito 2023). After World War II, the emphasis switched from military to civilian uses, which resulted in the construction of nuclear power plants and the development of nuclear medicine for diagnostic and therapeutic use (Baron and Herzog 2020; Högselius 2022).

Nuclear incidents such as the Chornobyl disaster in 1986 and the Fukushima Daiichi accident in 2011 underscored the risks linked to nuclear energy (Fig. 3), necessitating improved safety protocols and technological advancements (Magwood IV et al. 2021; Kaluha et al. 2020). Recent advancements focus on enhancing the safety and sustainability of nuclear technologies, exemplified by Generation IV nuclear reactors, which provide greater efficiency, enhanced safety features, and minimized waste (Potrč et al. 2021). Thorium and other alternative fuels are being evaluated for their availability and potential to generate reduced hazardous waste (Chroneos et al. 2023). The incorporation of advanced materials and technologies, such as biochar, offers significant potential for mitigating environmental and safety issues in nuclear science (Park et al. 2023).

2.2 Impacts of nuclear materials on health and environment

Though nuclear materials have immense benefits, inappropriate handling of them seriously affects the environment, wildlife, human health, and even the nuclear materials themselves (Donald 2010). Ionizing radiation exposure from nuclear events can have several unfavorable effects (Chaturvedi and Jain 2019). Radiation sickness brought on by acute exposure can present nausea, vomiting, tiredness, and hair loss (Sourati et al. 2017). Long-term exposure is much more hazardous since it alters DNA and increases the chance of leukemia, thyroid, breast, and lung cancers among others (Ali et al. 2020). Furthermore, genetic changes resulting from radiation exposure might influence next generations (Belli and Tabocchini 2020). Higher cancer rates in impacted communities are a result of the major health consequences of nuclear exposure shown by historical nuclear incidents such Chernobyl and Fukushima Daiichi (Hasegawa et al. 2015). These nuclear events have been well recorded, and depending on the type of incident, the effects vary greatly in degree and long-term results. For instance, the 1986 Chernobyl accident produced significant amounts of radioactive material that caused acute radiation sickness in scores of workers and resulted in 28 instantaneous fatalities (Symons 2008). With widespread contamination of soil, water, and ecosystems impacting genetic variations in plants and animals, the environmental impact was also severe (Møller and Mousseau 2011). Likewise, the 2011 Fukushima Daiichi accident produced radioactive isotopes that caused mass evacuations and extensive contamination of marine and agricultural ecosystems (WHO 2013; Steinhauser et al. 2014). Reduced fertility, developmental abnormalities, genetic alterations, and increased mortality rates were shown by radiation-exposed species in the Chernobyl and Fukushima exclusion zones (Cannon and Kiang 2022). Along with growing rates of defects and changed behavior in polluted places, studies have shown clear declines in the populations of birds, mammals, and insects (Møller and Mousseau 2011). Likewise, radiation-exposed plants

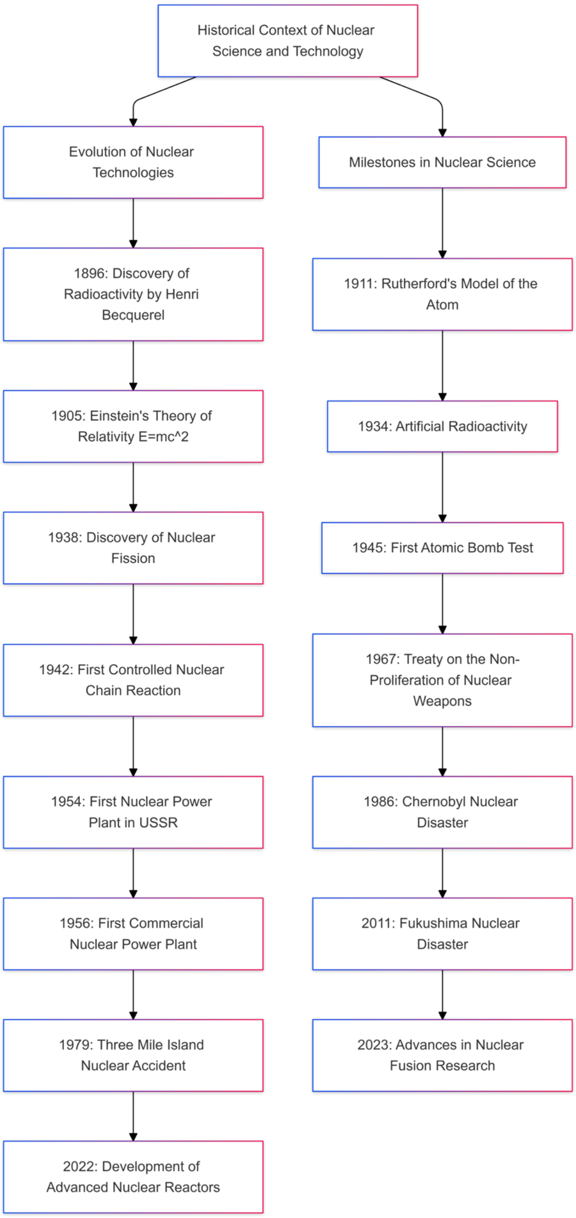


Fig. 3 Historical context of nuclear science and technology in the world (Bersano and Segantin 2024)

displayed reduced photosynthetic efficiency, morphological abnormalities, and slowed growth that can upset whole ecosystems and food chains (Kozubov and Taskaev 2007). Because of their lengthy half-lives, long-term radioactive emissions such cesium-137 and strontium-90 can remain in the environment for decades, therefore contaminating soil and water continually (Ješkovský et al. 2019). Radionuclide biomagnification and bioaccumulation raise the hazards much more for higher trophic level species including humans (Higley et al. 2012). Reducing these risks depends on good corrective actions. For nuclear waste remediation, for instance, biochar has showed promise since it can capture radionuclides and lower their bioavailability, thus fostering safer surroundings and so lowering health hazards (Datta et al. 2022). Emphasizing the need of strict safety measures, efficient waste management, and strong emergency readiness to lower future health and environmental hazards, these case studies highlight the terrible results of nuclear material mismanagement and radiation exposure.

3 The role of biochar in nuclear waste management

More and more people find biochar to be a sustainable and ecological solution for handling the challenging circumstances presented by radioactive pollutants in nuclear waste management (Adeola et al. 2022) (Fig. 4). Particularly useful in the adsorption of radioactive elements (Pipíška et al. 2020), biochar—a carbon-rich substance created by the pyrolysis of biomass—showcases specific characteristics that make it particularly effective.

3.1 Mechanisms of radioactive contaminant adsorption

As a sustainable and efficient way to address radioactive contamination in the disposal of nuclear waste, biochar is increasingly being known (Datta et al. 2022). Made from biomass by pyrolysis, biochar is a carbonaceous material with special qualities that improve its adsorbing ability of radioactive elements (Guilhen et al. 2019). Important elements facilitating this operation of the material are its large surface area and porosity (Leng et al. 2021). The large surface area and complex porous structure of biochar give a significant stage for radioactive contamination adsorption (Mathuriya et al. 2023). The linked network of holes greatly reduces the mobility of radionuclides, therefore lowering their danger of environmental contamination (Bhattacharya et al. 2024). Furthermore, a broad spectrum of different functional groups including phenolic, carboxyl, and hydroxyl groups define the biochar surface. By means of several approaches, including ion exchange and complexation (Liska et al. 2023), these groups interact with radioactive pollutants. On the surface of biochar (Shen et al. 2023), ion exchange is the process of substituting non-radioactive ions for radioactive ones.

Whereas complexation relates to the creation of long-lasting complexes between the functional groups of biochar and radioactive ions, a necessary mechanism for the selective retention of radionuclides. Chemical changes of biochar and advanced techniques have been shown to greatly improve its capacity for selective material adsorbability. For pollution adsorption (Murtaza et al. 2022), for example, the formation of complexes between metal

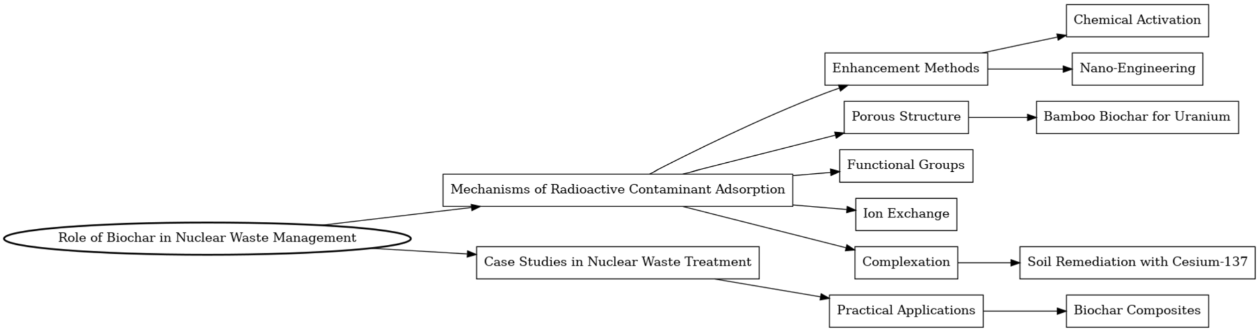


Fig. 4 Biochar: a sustainable solution for nuclear waste management (Guo et al. 2023a, b)

ions and oxygen-enriched functional groups on the biochar surface has been found to be a fundamental process. Moreover, the adsorptive ability and modification strategies of biochar have been thoroughly investigated to show how physicochemical characteristics and preparation processes affect its efficacy (Yang et al. 2019; Srivatsav et al. 2020).

Furthermore, studies on biochar made from water hyacinth have shown remarkable adsorption capacity for uranium (VI), thereby highlighting the possibilities of plant-derived biochar in addressing radioactive pollutants (Xu et al. 2020). Furthermore, the adsorption of heavy metals by complexation has been seen to be improved by the modification of biochar with phosphoric acid, therefore providing understanding of efficient biochar modification techniques for environmental remediation (Peng et al. 2017).

The combined data from these experiments show how well biochar captures a wide range of radioactive pollutants, therefore confirming its viability as a sustainable and reasonably priced method of managing nuclear waste (Hu et al. 2020). Constant research emphasizes how important biochar is to solve major obstacles in nuclear technology and environmental protection.

3.2 Case studies in nuclear waste management

Numerous studies have clearly shown the value of biochar in treating nuclear waste; it is flexible and efficient in adsorbing radionuclides from polluted surroundings, and provides sustainable remedies for nuclear rehabilitation. Using biochar derived from eucalyptus wood to remove uranium from aqueous solutions, Mishra et al. (2017) performed laboratory sorption studies finding that the eucalyptus biochar effectively adsorbed uranium with removal efficiencies reaching up to 90%, influenced by factors such as pH, contact time, and initial uranium concentration, thus highlighting the potential of eucalyptus-derived biochar in uranium remediation attempts. Similarly, Feng et al. (2024) examined the uranium adsorption efficiency of biochar produced at different pyrolysis temperatures ranging from 300 to 700 °C, revealing that biochar produced at 700 °C exhibited the highest uranium adsorption efficiency in contaminated soils due to enhanced surface area and porosity, stressing the critical role of pyrolysis temperature in optimizing biochar for nuclear waste treatment. A combination of techniques such as Fourier-transform infrared spectroscopy (FTIR) and surface complexation modeling clarified that uranium removal by biochar occurs primarily through surface complexation and ion exchange processes, thus offering valuable insights for designing biochar materials tailored for efficient uranium removal in nuclear wastewater treatment. Xu et al. (2024) used spectroscopic and modeling approaches to investigate the uranium adsorption properties of biochar.

By means of agricultural byproducts, Akl et al. (2021) created a hydrogel-biochar composite where the composite material greatly enhanced uranium removal rates compared to raw biochar, attaining removal efficiencies exceeding 95%, as the hydrogel matrix improved the dispersion of biochar particles and increased the availability of adsorption sites, thus offering a promising solution for remediating uranium-contaminated nuclear wastewater. With plant absorption of uranium lowering greatly in biochar-amended soils, indicating reduced ecological risks and highlighting the potential of biochar in in-situ remediation of uranium-contaminated environments, Huang et al. (2024) evaluated the effect of biochar on uranium retention and reduction in contaminated soil samples in field studies.

With the pyrolysis temperature being a crucial factor influencing adsorption efficiency due to enhanced surface area and pore structure at higher temperatures, Guilhen et al. (2019) investigated the pyrolysis of macauba-derived biochar at different temperatures and analyzed its uranium removal capacity from aqueous solutions, concluding that macauba biochar is effective in removing uranium. By means of oxidized biochar fibers, Stasi et al. (2022) conducted laboratory-scale tests to eliminate uranium from both laboratory-prepared and environmental water samples, demonstrating significant capacity for uranium removal, attaining up to 98% removal efficiency, as the enhanced surface functionality of the fibers enabled strong interactions with uranium ions, and is therefore appropriate for real-world scenarios involving uranium contamination in water. Liu et al. (2022) used hydrothermal carbonized reed straw to create low-cost biochar and investigated its uranium removal capacity in contaminated water. The reed straw biochar showed effective uranium adsorption and maximum capacities reaching 120 mg g^{-1}, suggesting that using agricultural waste materials like reed straw offers a sustainable and economical way to remediate nuclear wastewater.

Kimura et al. (2014) used biochar made from waste crops and animal manure to remove radioactive cesium (^{134}Cs and ^{137}Cs) from contaminated water, demonstrating high adsorption capacities for cesium ions and practical application in scenarios such as the Fukushima Daiichi nuclear disaster where cesium contamination is prevalent. With their stability and simplicity of handling, Jang et al. (2018) developed rice straw-based biochar beads for the removal of radioactive strontium (^{90}Sr) from aqueous solutions, demonstrating their potential for treating strontium-contaminated water, with which they fit for practical applications in nuclear waste management. Investigating the use of engineered bamboo biochar for the removal of pertechnetate ($^{99}TcO_4^-$) and perrhenate ($^{188}ReO_4^-$), analogs of radioactive technetium and rhenium, Daňo et al. (2021) found that biochar could effectively adsorb these radionuclides with removal efficiencies exceeding 80%, indicating biochar's potential in treating nuclear waste streams containing such contaminants.

Additionally, creative biochar changes to improve radionuclide adsorption are under investigation. Developing magnetic watermelon rind biochar for uranium removal, Lingamdinne et al. (2022) introduced magnetic properties that enabled simple separation of the biochar from treated water using an external magnetic field, and obtained uranium removal efficiencies of up to 99%, thus highlighting the advantages of biochar modification for enhanced radionuclide adsorption. Emphasizing that surface modifications such as doping with functional groups or nanoparticles greatly enhance adsorption capacities of biochar, Vidu et al. (2020) reviewed the potential of modified biochar-based materials in wastewater treatment, including the removal of heavy metals and radionuclides, offering tailored solutions for particular contaminants in nuclear waste streams. With higher temperatures generally enhancing adsorption efficiency due to increased surface area and pore volume, these studies collectively highlight the potential of biochar as a sustainable and effective material for nuclear waste management, demonstrating versatility in adsorbing a wide range of radionuclides including uranium, cesium, strontium, technetium, and rhenium, and highlight the importance of pyrolyzed conditions, particularly temperature, which significantly affect the structural properties and adsorption capacity of biochar. The adsorption performance and practical relevance of biochar are much improved by means of modification including oxidation, composite development, or addition of magnetic characteristics. Using different biomass sources—including waste products and agricultural by-products—for biochar generation helps to be cost-effective and sustainable; laboratory and field studies have shown that biochar can efficiently immobilize radionuclides in soils and water, thus lowering environmental hazards and supporting remedial initiatives.

Moreover, the combination of spectroscopic and modeling techniques offers important new perspectives on the mechanisms of radionuclide adsorption by biochar, exposing the major roles of surface complexation, ion exchange, and physical adsorption in the removal of radioactive contaminants. As shown by Akl et al. (2021) and Lingamdinne et al. (2022), the use of biochar in composite materials creates fresh opportunities for the development of innovative materials with exceptional adsorption capacity and functions customized to meet particular remedial needs. By lowering the mobility and bioavailability of hazardous radionuclides in contaminated environments, these results have practical ramifications that go beyond cost-effective, sustainable, and efficient solutions for nuclear waste management to help environmental protection.

The combined data from these case studies not only underline the efficiency of biochar in nuclear waste treatment but also underline the need of more research to maximize biochar production processes, investigate many biomass sources, and create advanced biochar-based materials with enhanced properties. The scalability of biochar manufacture and its integration into current nuclear waste management systems offer chances for general application, thus transforming the method of nuclear cleanup and helping to progress sustainable nuclear technologies. Using the special qualities of biochar and its adaptability through changes helps one to solve the difficult issues related to nuclear waste, thereby supporting environmental sustainability and safety in the nuclear sector.

Despite the promising applications of biochar in nuclear waste management, several critical issues need to be addressed to advance its practical implementation. One significant concern is the lack of understanding regarding the interaction mechanisms between specific radionuclides and different types of biochar. While general mechanisms like adsorption and ion exchange are recognized, the influence of physicochemical properties of biochar on the adsorption of particular radionuclides, such as technetium-99 or iodine-129, remains underexplored (Hu et al. 2020). Detailed studies focusing on radionuclide-specific interactions are necessary to optimize biochar for targeted nuclear waste remediation.

Another challenge lies in the regeneration and disposal of spent biochar loaded with radionuclides. The management of radioactive biochar after it has been used for adsorption is a critical aspect that requires careful consideration. Strategies for the safe handling, storage, or potential reuse of radionuclide-laden biochar are not well-developed (Panwar 2024). Research into thermal treatment, immobilization techniques, or encapsulation methods could provide solutions for managing spent biochar while minimizing secondary waste generation.

Furthermore, the scalability of biochar production presents practical limitations. Producing biochar with consistent quality and properties at a scale sufficient for large nuclear remediation projects is challenging. Variability in feedstock availability, differences in biomass composition, and the energy requirements of pyrolysis processes can affect the feasibility and cost-effectiveness of large-scale biochar applications. Developing standardized production protocols and exploring alternative feedstocks, such as agricultural residues or dedicated energy crops, could mitigate these issues (Zhao et al. 2023).

Environmental regulations and public perception also pose barriers to the adoption of biochar in nuclear waste management. There may be concerns about introducing biochar into the environment, particularly regarding its long-term impact on soil health and ecosystems. Additionally, stakeholders may be hesitant to accept biochar applications near sensitive areas due to fears of unintended consequences. Engaging with regulatory bodies, conducting comprehensive environmental impact assessments, and fostering transparent communication with the public are essential steps to address these concerns (Gorovtsov et al. 2020).

Lastly, economic analyses of biochar use in nuclear remediation are limited. While biochar is often touted as a cost-effective solution, detailed cost–benefit analyses considering production, transportation, application, and post-treatment management are lacking. Understanding the economic implications is crucial for decision-makers when comparing biochar to alternative remediation technologies (Nkoh et al. 2021).

4 Biochar for radiation shielding: a novel approach

4.1 Properties and effectiveness

Investigating biochar in the context of radiation shielding in nuclear physics is a fresh and exciting endeavour, deviating from its conventional uses in agriculture and carbon sequestration to a potential guardian against ionising radiation. The inherent qualities of biochar anchor this creative change and make it a good shield material (Borgohain et al. 2023). Mostly made of carbon, the layered and thick structure of biochar is essential for radiation shielding. With its dense molecular arrangement offering a strong barrier against radiation penetration, this high carbon content is essential in reducing and absorbing several types of ionizing radiation, including gamma ray (Kaur et al. 2019; Yasmin et al. 2018). Biochar is unique among typical shielding materials such as lead or concrete in that it is flexible and lightweight (Amanu 2022). In situations requiring mobility and simplicity of handling, including the design of portable radiation shields or protective gear for workers in nuclear facilities, this feature is especially helpful. Beyond its practical benefits, biochar is a byproduct of biomass waste, and hence it is a sustainable and environmentally friendly choice for radiation protection (Natalio et al. 2020). Its manufacture and use provide a greener substitute for more dangerous elements like lead, in line with aims of ecological preservation. Using biochar as a component in composite materials increases its potential in radiation protection even more.

Its shielding qualities can be greatly improved by combining biochar with other radiation-absorbing compounds or embedding it in different matrices (Allahkarami and Allahkarami 2024; Huang et al. 2019). These composites are designed to target particular radiation levels, hence improving their protective properties. Furthermore, a reasonably priced method for radiation protection is the generation of biochar from biomass waste (Tareq et al. 2019). Biochar provides a cheap substitute without sacrificing efficacy unlike conventional materials, which can be costly and resource-intensive to create. Uncovering and enhancing the radiation-shielding qualities of biochar is the main concentration of current research and development. These investigations cover testing biochar under various situations, altering its characteristics by physical and chemical processes, and evaluating its efficacy across many radiation shielding uses (Natalio et al. 2020; Sutton et al. 2021; Kumar et al. 2022). Ultimately, the use of biochar for radiation protection is a novel strategy based on its inherent qualities for protective needs. Biochar shows great potential as an efficient, sustainable, and reasonably priced material for shielding against ionizing radiation (Sutton et al. 2021), even if research and development are still in their early years.

Its possible uses cover nuclear reactors, medical environments, and space exploration, generating great interest in the search of safer and ecologically friendly radiation protection systems (Fig. 5).

The significant enhancement of shielding properties in biochar-based materials stems from their ability to incorporate and synergize with other radiation-attenuating substances, resulting in composites that are effective against various types of ionizing radiation while aligning with sustainability and cost-efficiency goals. When biochar is used in composite materials, its porous structure and large surface area allow it to host high atomic number (Z) materials—such as metal oxides or nanoparticles like lead, bismuth, or tungsten—thereby gaining the high-density characteristics necessary for effective gamma radiation shielding (Torsello et al. 2021). These high-Z materials enhance photon attenuation mechanisms, specifically the photoelectric effect and Compton scattering processes, which are critical for absorbing and deflecting gamma photons; when embedded within biochar, the overall attenuation coefficient of the composite increases (Nikolopoulos et al. 2023). Additionally, biochar contains light elements like hydrogen and carbon, effective at slowing down fast neutrons through elastic scattering, and incorporating boron or lithium compounds can further enhance neutron absorption due to their high neutron capture cross-sections. The structural advantages of biochar, such as its porosity and surface area, facilitate the uniform distribution of added shielding agents, ensuring consistent shielding performance throughout the material (Thibeault et al. 2012). Its customizable matrix allows for chemical and physical modifications through processes like activation or doping, optimizing the shielding capabilities of composite for specific radiation types. Even with added high-density materials, biochar-based composites remain lighter than traditional shielding materials like lead or concrete, making them suitable for applications where weight and flexibility are crucial, such as in protective gear or space vehicles (Zhang et al. 2022b). Environmentally, utilizing biochar—a byproduct of biomass waste—aligns with conservation efforts by reducing reliance on hazardous materials and promoting waste valorization, while economically, producing these composites is less resource-intensive and cheaper than manufacturing traditional shielding materials (Feliz Florian et al. 2024). Tailored shielding solutions are achievable by selecting specific additives and adjusting their concentrations within the biochar matrix, engineering composites to target and optimize protection against specific types of

Fig. 5 Innovative radiation shielding with biochar: properties, R&D process, and comparative analysis (Martellucci and Torsello 2022; Barbhuiya et al. 2024)

radiation, and chemical treatments can introduce functional groups to biochar, enhancing its ability to bind with metal ions or nanoparticles, thus improving its radiation attenuation properties (Mohtaram et al. 2024). Research and development insights include experimental validation demonstrating that biochar-based composites exhibit higher mass attenuation coefficients compared to pure biochar or traditional materials, confirming their enhanced shielding effectiveness, and advanced modeling techniques used to predict and optimize the shielding performance of biochar composites under different conditions, guiding the development of more effective materials (Torsello et al. 2021; Martellucci and Torsello 2022). Applications span medical settings where biochar composites can be used in shielding materials for medical imaging or radiation therapy rooms, nuclear facilities where lightweight biochar-based shields enhance safety for personnel, and space exploration where the need for lightweight, effective shielding materials makes biochar composites attractive for protecting spacecraft and astronauts from cosmic radiation (Torsello et al. 2021).

4.2 Comparative analysis with traditional shielding materials

In the realm of radiation shielding, a comparative analysis between biochar and traditional materials such as lead, concrete, or boron-containing compounds highlights the unique advantages and challenges of biochar. Lead, historically the preferred choice for radiation shielding due to its high density and effectiveness in blocking gamma rays, is hampered by significant drawbacks including its considerable weight, inflexibility, and particularly its toxicity, which poses serious environmental and health risks (McCaffrey et al. 2007; Chandrika et al. 2023). Biochar, in stark contrast, is non-toxic, lightweight, and environmentally sustainable, offering a safer handling and disposal option, despite possibly not matching the shielding effectiveness of lead per unit thickness(Zhang and Lin 2023; Appusamy et al. 2021). Concrete, another widely used material in nuclear facilities for its structural and shielding properties, especially against neutron radiation, is limited by its heavy weight, rendering it unsuitable for mobile or temporary shielding solutions. Here, the much lighter nature of biochar provides distinct advantages in scenarios demanding mobility or where structural weight is a concern. However, inherent properties of biochar do not offer the same level of neutron absorption as boron compounds, but its potential integration with boron or other neutron-absorbing materials in composite forms could harness the benefits of both (Favero 2020).

From a cost and availability perspective, traditional materials like lead and concrete are often expensive and resource-intensive to produce, whereas biochar, derived from biomass waste, emerges as a more cost-effective and readily available alternative, with a production process that is more aligned with environmental sustainability (Kurniawan et al. 2023). The flexibility of biochar in terms of modifications and its potential for use in composite materials enhances its versatility as a radiation shielding option, allowing it to be engineered to improve specific shielding properties or combined with other materials to target different radiation types (Amanu 2022; Sutton 2021). The environmental impact of traditional shielding materials, particularly lead, is a significant concern, whereas biochar stands out as a carbon-negative material, potentially contributing to carbon sequestration and aligning with broader environmental sustainability goals.

Despite the established protocols and long history of traditional materials in radiation shielding, biochar is a relatively new entrant in this field. Ongoing research is vital to fully comprehend its capabilities, limitations, and the possibilities for enhancing its effectiveness in radiation shielding. While traditional materials like lead, concrete, and boron-containing compounds have proven their effectiveness in radiation shielding (Zhang and Lin 2023), biochar presents itself as a novel, environmentally friendly, and potentially safer alternative. Its lightweight, flexible, and sustainable nature, combined with the potential for modifications and use in composites, positions biochar as a promising material in the field of radiation protection (Martellucci and Torsello 2022; Devi et al. 2022). However, the necessity for further research and development is paramount to optimize its properties and establish its efficacy across various shielding applications, marking a significant step towards safer and more environmentally responsible radiation shielding solutions.

4.3 Case studies in radiation shielding

Case studies in biochar radiation shielding have provided practical insights into the effectiveness and potential real-world applications of biochar in radiation protection, showcasing its innovative use in various forms and composites. Natalio et al. (2020) developed sustainable, lightweight biochar-based composites with electromagnetic shielding properties by producing biochar from pine wood through pyrolysis at 800 °C and incorporating it into a polymer matrix to form composites with varying biochar content (10%, 20%, and 30% by weight). The composites were subjected to electromagnetic interference (EMI) shielding effectiveness tests across a frequency range of 8–12 GHz (X-band), and findings indicated that the biochar-polymer composites exhibited increased EMI shielding effectiveness with higher biochar content, achieving up to 30 dB shielding effectiveness at 30% biochar content, effectively attenuating 99.9% of incident radiation in the X-band frequency while maintaining good mechanical properties and lightweight characteristics compared to traditional shielding materials. This demonstrated the potential of biochar in creating materials suitable for electromagnetic radiation shielding, highlighting its applicability in developing sustainable shielding materials for electronic devices and infrastructure.

Martellucci and Torsello (2022) evaluated the potential of biochar-reinforced concrete as a neutron shielding material by adding biochar derived from agricultural waste to concrete mixes in different proportions (0%, 5%, 10%, and 15% by volume). The neutron shielding effectiveness was assessed using a neutron source, measuring the attenuation of neutron radiation through the concrete samples. The findings revealed that the addition of biochar improved the neutron attenuation properties of concrete, with the 15% biochar concrete reducing neutron radiation by up to 20% compared to standard concrete, while also exhibiting satisfactory mechanical properties for structural applications. This suggests that biochar–concrete composites could enhance safety in nuclear facilities by improving neutron shielding while reducing reliance on heavier traditional materials.

Sutton et al. (2021) developed fluorine-intercalated biochar materials for radiation shielding applications by producing biochar from hardwood biomass, chemically intercalating it with fluorine atoms, and incorporating the modified biochar into a flexible matrix to create lightweight shielding materials. Radiation shielding effectiveness was tested against gamma rays using a Cs-137 gamma source, and the findings showed that the fluorine-intercalated biochar exhibited enhanced attenuation of gamma radiation compared to unmodified biochar, reducing gamma radiation exposure by up to 25%. The material was lightweight and flexible, suitable for protective clothing or portable shielding devices, demonstrating that chemical modification of biochar can enhance its radiation shielding properties and highlighting its potential in developing flexible shielding materials for personal protection in nuclear environments.

Devi et al. (2022) fabricated biochar composites incorporating heavy metal oxides for improved gamma radiation shielding by producing biochar from red onion husk through pyrolysis and combining it with cobalt and carbon fibers in a polyvinyl alcohol (PVA) matrix to create composite materials. The composites were tested for electromagnetic interference shielding in the X and Ku band frequencies and evaluated for gamma radiation shielding effectiveness. The findings indicated that the biochar composites showed significant improvements in electromagnetic shielding effectiveness, with the presence of cobalt and carbon fibers enhancing the attenuation of gamma radiation. The composites maintained good flexibility and could be molded into various shapes, showing that incorporating heavy metal oxides into biochar composites can improve gamma radiation shielding and providing a pathway for developing multifunctional materials offering both electromagnetic and gamma radiation protection.

Natalio et al. (2020) explored the use of biochar composites for radiation shielding in space exploration by using biochar derived from plant biomass to create composites with polymers suitable for aerospace applications. The composites were evaluated for their ability to shield against cosmic radiation, including high-energy particles, and were assessed for mechanical properties relevant to space materials, such as tensile strength and thermal stability. The findings demonstrated that the biochar composites could attenuate cosmic radiation, reducing the dose equivalent of high-energy particles, and exhibit adequate mechanical strength and thermal stability for space environments. The lightweight nature of the composites offered significant advantages in reducing payload weight for space missions, suggesting that biochar-based materials could be used to develop lightweight radiation shields for spacecraft and habitats, contributing to sustainable materials in the aerospace industry.

Comparative analyses with traditional shielding materials highlight the unique advantages and challenges of biochar. Zhang and Lin (2023) assessed the environmental impact and radiation shielding effectiveness of biochar-based materials compared to traditional lead shielding by conducting life cycle assessments (LCA) of biochar production and lead extraction processes, evaluating gamma radiation shielding effectiveness of biochar composites and lead plates of equivalent thickness, and analyzing environmental and health risks associated with their use and disposal. The findings showed that biochar composites provided satisfactory radiation attenuation and, although slightly less effective per unit thickness compared to lead, they had a significantly lower environmental impact and posed minimal health risks during handling and disposal, unlike lead. This highlighted the trade-offs between shielding effectiveness and environmental impact, supporting the adoption of biochar composites where moderate shielding suffices and environmental sustainability is prioritized.

Favero (2020) enhanced the neutron absorption capabilities of biochar by incorporating boron compounds to create biochar–boron composites. Neutron shielding effectiveness was tested using a neutron radiation source, and the composites were compared to traditional boron-containing shielding materials. The findings indicated that the biochar–boron composites showed improved neutron absorption compared to pure biochar, providing a lightweight alternative with acceptable performance while maintaining the environmental benefits of biochar. This demonstrated that modifying biochar with neutron-absorbing elements enhances its applicability in neutron radiation shielding, suggesting potential for biochar-based materials in applications requiring both neutron and gamma radiation protection.

Kurniawan et al. (2023) evaluated the cost-effectiveness of using biochar as a radiation shielding material compared to traditional materials like lead and concrete by analyzing production costs of biochar from various biomass wastes, comparing material costs, manufacturing expenses, and lifecycle costs, and considering additional factors such as transportation, installation, and disposal costs. The findings revealed that biochar-based shielding materials were more cost-effective when considering the entire lifecycle, especially where lightweight materials reduce transportation and installation expenses, supporting the economic viability of biochar as a radiation shielding material.

Amanu (2022) assessed the mechanical properties of biochar/high-density polyethylene (HDPE) composites for electromagnetic shielding applications, finding that the composites exhibited improved mechanical properties compared to pure HDPE and enhanced electromagnetic shielding effectiveness, suitable for structural applications requiring both mechanical strength and radiation protection. Finally, Zhang et al. (2022b) evaluated biochar as a construction material contributing to carbon neutrality while providing radiation shielding, finding that biochar-infused concrete contributed to carbon sequestration and offered adequate radiation shielding properties for certain applications, highlighting the dual benefits of using biochar in construction for both environmental sustainability and radiation protection.

These case studies collectively demonstrate the potential of biochar as a sustainable, cost-effective, and adaptable material for radiation shielding, offering significant advantages over traditional materials in terms of environmental impact, flexibility, and potential for enhancement through modifications and composites. the lightweight and flexible nature of biochar makes it suitable for applications where mobility and ease of handling are essential, such as portable shields or protective gear, and its ability to be engineered into composites allows for targeting specific radiation types and optimizing protective capabilities. While biochar may not match the shielding effectiveness of traditional materials like lead per unit thickness, its environmental benefits, lower health risks, and cost-effectiveness make it a promising alternative, especially in applications where moderate shielding suffices. The incorporation of biochar into construction materials not only contributes to radiation protection but also aids in carbon sequestration, aligning with global sustainability goals. Modifying biochar with elements like fluorine or boron further enhances its shielding properties, expanding its applicability to neutron and gamma radiation protection. The collective evidence from these studies highlights the need for continued research and development to optimize the properties of biochar and establish standardized methods for its use in radiation shielding, ultimately positioning biochar as a promising material in the pursuit of safer and more environmentally responsible radiation protection solutions.

While biochar shows promise as a radiation shielding material due to its environmental advantages, versatility, and cost-effectiveness, existing research reveals several critical considerations that must be addressed. The effectiveness of biochar in radiation shielding varies significantly depending on the type of radiation, biochar feedstock, production methods, and modifications; studies like those by Devi et al. (2022) and Martellucci and Torsello (2022) have demonstrated enhanced shielding with biochar composites, but results are not yet consistent enough for standardized application. Additionally, the fundamental mechanisms by which biochar attenuates different types of radiation are not fully understood—while high carbon content contributes to gamma-ray attenuation, the roles of the microstructure and potential of biochar for neutron moderation require further investigation. Research indicates that pure biochar may not provide sufficient shielding on its own, necessitating modifications such as incorporating heavy metals or neutron-absorbing elements like boron to enhance effectiveness (Favero 2020); however, introducing such elements may compromise some environmental benefits. Concerns also exist regarding the long-term durability and stability of biochar under radiation exposure and environmental conditions, as potential degradation could affect shielding performance over time (Zhang and Lin 2023). Moreover, most studies have been conducted at the laboratory scale, presenting significant challenges in scaling up production and fabrication of biochar-based shielding materials while maintaining quality and performance (Kurniawan et al. 2023). To overcome these challenges, future directions should focus on intensifying research and development on biochar modifications and composite materials, conducting larger-scale experiments and field trials to evaluate practical feasibility and long-term stability, performing comprehensive environmental and economic assessments to validate sustainability claims and cost benefits, and encouraging interdisciplinary collaboration among material scientists, nuclear engineers, and environmental experts, supported by adequate funding and policy support to address regulatory requirements and ensure safe, standardized implementation of biochar-based shielding materials in the industry.

5 Biochar as a catalyst in environmental remediation

5.1 Surface area and porosity

Made from biomass pyrolyzed, biochar is distinguished by its great surface area and great porosity, which makes it a very powerful catalyst for chemical reactions—especially in environmental uses (Wang and Wang 2019). The vast surface area of the porous structure—which features mesopores and micropores—helps to improve the interaction between reactants and active catalytic sites (Tan et al. 2015). Higher reaction rates resulting from this enhanced contact are especially seen in heterogeneous catalysis, where biochar supports metal catalysts (Rodriguez-Narvaez et al. 2019). In environmental settings, such water treatment, the porous character of biochar helps it to absorb heavy metals and organic contaminants, so enhancing their catalytic breakdown (Inyang et al. 2016). The great surface area also helps metal nanoparticles to be uniformly distributed, therefore avoiding agglomeration and preserving catalytic activity throughout lengthy use (Wang et al. 2021). For instance, whereas biochar-supported nickel catalysts improve hydrogen generation via reforming techniques, biochar-supported iron catalysts have been effectively used in Fenton-like reactions to breakdown organic contaminants (Deng et al. 2020b). In sustainable environmental remediation, the porous biochar structure not only improves the accessibility of contaminants to catalytic sites but also stabilizes the catalytic particles, therefore rendering this material flexible. Thus, especially in the breakdown of contaminants and hydrogen generation, biochar's great surface area and porosity are absolutely critical in enhancing catalytic processes.

5.2 Functional groups

The surface of biochar contains a variety of functional groups, including hydroxyl, carboxyl, and phenolic groups, which significantly enhance its catalytic properties (Table 2) (Wang and Wang 2019). These functional groups are critical in facilitating the adsorption and interaction of pollutants with the biochar surface, enabling catalytic reactions such as ion exchange, complexation, and advanced oxidation processes (Tan et al. 2015). In environmental applications, the presence of these functional groups allows biochar to act as an efficient catalyst or catalyst support, particularly for the degradation of organic pollutants and the removal of heavy metals (Mohan et al. 2014). For example, biochar functionalized with iron oxides enhances its catalytic ability to generate reactive oxygen species in Fenton-like reactions, which degrade complex pollutants in water (Li et al. 2020c). Moreover, the functional groups on biochar enable strong interactions with pollutants, promoting their adsorption and subsequent catalytic degradation (Chen et al. 2011). This is especially effective in water treatment and soil remediation, where biochar not only adsorbs contaminants but also participates actively in their breakdown (Ahmad et al. 2014). The versatility of these functional groups allows for the modification and functionalization of biochar to optimize its catalytic performance for specific environmental challenges, including pollutant degradation, heavy metal removal, and even carbon capture and sequestration (Liu et al. 2015).

5.3 Heterogeneous catalysis

Essential in environmental and industrial chemical processes, biochar's heterogeneous catalyst function is in stabilizing and dispersing catalytic particles (Liu et al. 2015). Its high surface area and porous shape help metal nanoparticles to be uniformly dispersed, thereby avoiding their aggregation and guaranteeing constant catalytic activity (Zhang et al. 2022a). In heterogeneous catalysis, where it serves both as a catalyst and a support material for metals such iron, copper, and nickel, this makes biochar very useful (Lateef et al. 2019). Biochar-supported iron catalysts are often utilized in Fenton-like reactions in pollution degradation to produce reactive species that breakdown organic contaminants in wastewater (Deng et al. 2020b). Biochar promotes nickel and cobalt catalysts in reforming operations converting biomass or biogas into hydrogen gas (Wang et al. 2022b). Furthermore underlining biochar's adaptability in tackling environmental problems is its capacity to operate as a catalyst in carbon dioxide reduction reactions, wherein CO_2 is

Table 2 Summary of biochar characteristics from different feedstocks

Feedstock	Pyrolysis temperature (°C)	Surface area ($m^2\ g^{-1}$)	Pore volume ($cm^3\ g^{-1}$)	Functional groups
Wood chips	500	350	0.25	Hydroxyl, carboxyl
Rice husk	600	420	0.30	Carbonyl, ether
Sewage sludge	700	300	0.20	Amino, sulfonic
Coconut shell	800	500	0.35	Aromatic, phenolic

Data adapted from Xu et al. (2013), Jagadeesh and Sundaram (2023), and Prauchner and Rodríguez-Reinoso (2012) transformed into valuable molecules like methane or methanol (Zhang et al. 2022a). Biochar increases reaction efficiency and sustainability by changing the dispersion and stability of active catalytic sites (Liu et al. 2015). Its application in heterogeneous catalysis offers a reasonably affordable and environmentally benign method for carbon dioxide reduction, hydrogen generation, and pollution degradation (Wang and Wang 2019).

5.4 Photocatalysis

Using biochar as an adsorbent (Zhang et al. 2024), its capacity to support photocatalytic materials—such as titanium dioxide (TiO_2) or zinc oxide (ZnO)—capitalizes on this ability in photocatalysis. Biochar improves the breakdown of pollutants including organic dyes and pharmaceuticals under light irradiation by increasing the exposure of contaminants to light-activated catalytic sites in photocatalysis (Wong 2020). For instance, biochar–TiO_2 composites have been demonstrated to promote the photocatalytic breakdown of methylene blue dye, in which case the biochar not only improves light absorption and pollutant interaction but also helps to better dispersion of TiO_2 (Chandra et al. 2021). Increased light penetration and more pollution absorption made possible by the porous structure of biochar help to improve the effectiveness of the photocatalytic process by means of which pollution is absorbed (Lu et al. 2022). Furthermore, biochar can trap contaminants on its surface and bring them near to the active photocatalytic sites, therefore facilitating more effective breakdown (Ahmaruzzaman 2021). This makes biochar-based photocatalysts especially useful in environmental applications, such as wastewater treatment, where the elimination of dangerous contaminants is a top goal (Chandra et al. 2021). Biochar helps to more effectively and sustainably enhance the dispersion of photocatalysts and enable pollution absorption (Wang and Wang 2019).

5.5 Biochar as a catalyst for nuclear applications

Biochar exhibits catalytic properties that are essential in nuclear applications, especially in improving processes associated with radioactive waste management and environmental remediation (Huang et al. 2024). The elevated surface area and porosity of biochar, along with its varied functional groups, make it particularly effective in facilitating reactions crucial for nuclear waste treatment. Studies have shown that biochar produced from eucalyptus wood and various agricultural by-products effectively removes uranium from contaminated water and soils (Guilhen et al. 2019; Kimura et al. 2014). Research indicates that the adsorption and immobilization of uranium by biochar are notably affected by pyrolysis temperature, with elevated temperatures typically enhancing its catalytic performance (Datta et al. 2022; Leng et al. 2021). Biochar effectively facilitates advanced oxidation processes and complexation reactions, rendering it suitable for the treatment of nuclear wastewater by aiding in the breakdown of radioactive contaminants into less harmful forms (Shen et al. 2023). Furthermore, biochar contributes to the stability and efficacy of various catalysts utilized in nuclear applications, including those for the detoxification of radioactive substances (Liu et al. 2024). The development of biochar-based composites and their integration into catalytic systems highlights their potential in addressing significant challenges in nuclear science, providing a sustainable and efficient method for managing radioactive waste and enhancing environmental safety (Borgohain et al. 2023; Xu et al. 2020).

Biochar holds significant promise as a catalyst in environmental remediation, but its inherent variability—due to differences in biomass feedstocks, pyrolysis conditions, and chemical modifications—leads to inconsistencies that complicate large-scale applications (Lehmann and Joseph 2024; Kookana et al. 2011). This variability, coupled with an incomplete understanding of the mechanisms behind its catalytic processes involving functional groups, minerals, and pore structures, hinders optimization for targeted interventions (Ahmad et al. 2012). Challenges in catalyst regeneration and reusability arise because biochar can undergo structural changes or fouling after multiple uses, limiting its long-term applicability and necessitating economically feasible regeneration techniques (Inyang et al. 2016). Environmental concerns, especially in nuclear and chemical settings, include the risk of secondary contamination from sorbed contaminants like heavy metals or radionuclides under fluctuating conditions (Beesley et al. 2011). Additionally, the energy-intensive and greenhouse gas emissions associated with high-temperature pyrolysis used in biochar production underscore the need for more sustainable methods (Azargohar and Dalai 2006). Economically, while biochar production from agricultural waste appears cost-effective, uncertainties remain about the expenses associated with modifying, applying, and maintaining it at larger scales, warranting further techno-economic assessments (Shackley et al. 2009). Expanding applications of biochar into areas like electro-catalysis or enhancing photocatalytic performance with nanomaterials presents untapped opportunities (Leng et al. 2019). To advance its role in environmental remediation, targeted enhancements such as designing biochar with controlled porosity or doping with specific elements are needed, alongside strategic research, technology development, and interdisciplinary collaboration among researchers, industry experts, and policymakers to establish industry standards and improve regulatory frameworks (Sun et al. 2011).

6 Advanced production techniques of nuclear-grade biochar

6.1 Tailoring biochar for nuclear applications

Advancements in production techniques for nuclear-grade biochar are pivotal in enhancing its applications in nuclear settings, such as radioactive waste adsorption (Laili et al. 2015), radiation shielding (Natalio et al. 2020), and reactor moderation. These developments necessitate refining physical and chemical characteristics of biochar to optimize its nuclear performance (Martellucci and Torsello 2022). Central to this is the pyrolysis process, where biomass is heated in an oxygen-limited environment. Precise control over pyrolysis conditions—including temperature, heating rate, and duration—significantly influences the surface area, porosity, and functional group content of the resulting biochar (Leng et al. 2019). Higher pyrolysis temperatures typically produce biochar with greater surface area and porosity, thereby improving its radioactive material adsorption capabilities (Hassan et al. 2020). The choice of biomass feedstock is also crucial, as different organic materials—from agricultural residues to forestry waste—impart distinct properties to the biochar (Song et al. 2022). For example, biochar derived from hardwood differs in characteristics from that produced from coconut shells or rice husks.

Post-pyrolysis, further processing of biochar can enhance its properties (Chacón et al. 2020). Chemical activation using agents like potassium hydroxide or phosphoric acid increases pore volume and surface area, making biochar more effective in adsorbing radioactive materials. Impregnating biochar with elements such as boron enhances its neutron-absorbing capabilities, making it more suitable for nuclear reactor applications (Lazzarini et al. 2023). Nanotechnology opens new avenues for biochar modification, where engineering biochar at the nanoscale creates nanostructured materials with enhanced adsorption properties and specific affinities for certain radionuclides, leading to the production of biochar highly specialized for nuclear waste treatment (Kumar et al. 2020).

The development of biochar-based composites incorporating materials like metal oxides or other adsorptive substances significantly boosts the utility of biochar in nuclear applications, enhancing its performance in radioactive waste treatment or radiation shielding (Borgohain et al. 2023). Ensuring consistent quality and standardization of nuclear-grade biochar is essential, necessitating established protocols for production, characterization, and testing to meet the stringent requirements of nuclear applications. A major challenge in biochar production is scalability—the ability to scale up production to industrial levels while maintaining the desired properties of biochar (Pierson et al. 2024). Moreover, the production process should be environmentally sustainable, utilizing renewable biomass sources and minimizing emissions and waste (Usmani et al. 2021).

6.2 Innovations in biochar synthesis

Significant studies and improvements are being invested in the field of biochar synthesis, aiming to enhance its efficiency, scalability, and eco-friendliness, thereby increasing its use in areas like agriculture, environmental cleanup, and energy (Fig. 6). A notable innovation in this area is Microwave-Assisted Pyrolysis, which employs microwave energy to heat biomass, providing a more consistent and controlled heating process than traditional pyrolysis (Liu et al. 2020). This approach not only guarantees uniform, high-quality biochar but also helps reduce the energy required for the pyrolysis process. Co-pyrolysis is another advanced method that heats various feedstocks together, such as mixing biomass with plastic waste or other organics. This improves thecharacteristics of biochar—like porosity or nutrient levels—making it more suitable for specific uses like soil enhancement or pollutant absorption (Murtaza et al. 2023).

Hydrothermal Carbonization (HTC) is an innovative process that transforms biomass into biochar under high pressure and in the presence of water, making it especially effective for wet biomass (Aragón-Briceño et al. 2021). HTC produces hydrochar, which differs from traditionally pyrolyzed biochar and is often richer in nutrients, making it useful for agricultural applications. Combining biochar manufacturing with biomass gasification—which transforms organic materials into syngas and biochar—improves the overall energy efficiency of biomass use (You et al. 2018). This combination not only produces biochar but also creates a clean, renewable energy source. Recent advancements have also explored the use of biochar as a catalyst or support in chemical reactions, utilizing its substantial surface area and porosity to develop new avenues in green chemistry and renewable energy.

Material science improvements have led to the creation of engineered biochars tailored for specific uses by enhancing or modifying their properties. This includes infusing biochar with nutrients or minerals, tweaking its surface chemistry to boost adsorption capabilities, or developing biochar-based composites with superior mechanical or chemical properties (Yasim-Anuar et al. 2022; Saha et al. 2010). The introduction of automated and continuous biochar manufacturing systems is an

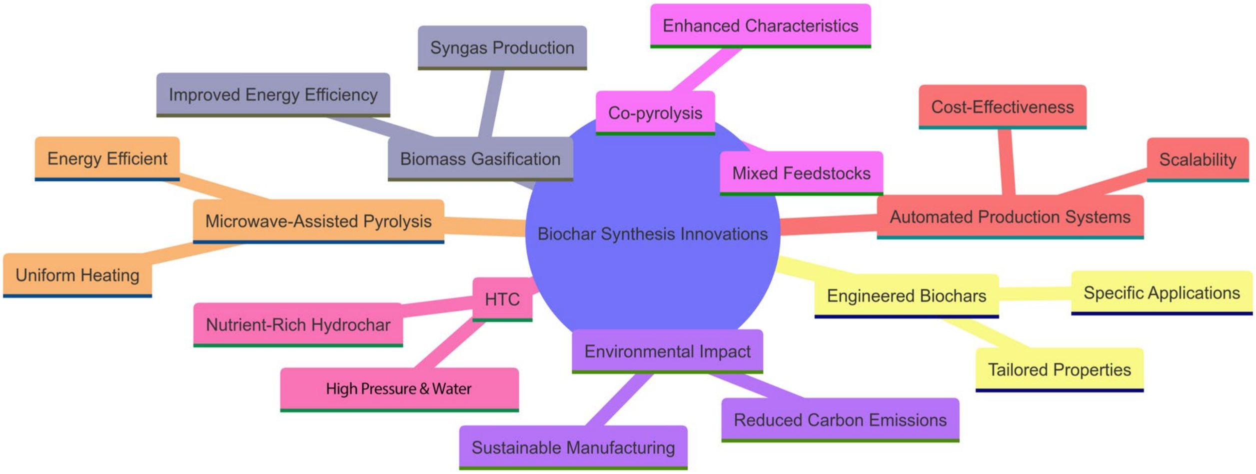


Fig. 6 Advancements in biochar production technologies (Giorcelli et al. 2021; Abnisa and Daud 2014)

exceptional innovation aimed at improving the scalability and efficiency of biochar production. These systems allow for more consistent and cost-effective processing of large biomass quantities, facilitating the feasibility of large-scale biochar production.

Additionally, biochar synthesis improvements consider the environmental impact and life cycle assessment (LCA) of its manufacturing, focusing on optimizing techniques to reduce carbon emissions, energy use, and waste, thereby ensuring the sustainability of biochar production (Zhu et al. 2022; Carvalho et al. 2022). These advancements are vital in enhancing the versatility and effectiveness of biochar, broadening its applications in environmental management, sustainable agriculture, and renewable energy. Ongoing upgrades in biochar production techniques are unlocking the full potential of this diverse material, establishing it as a vital element in sustainable practices and technological development across various sectors. This progress in biochar synthesis not only emphasizes its current importance in environmental and agricultural applications but also underscores its role in contributing to sustainable energy solutions and innovative industrial processes.

7 Characterization and testing of biochar in nuclear environments

7.1 Analytical methods for radioactive environments

In nuclear settings, the characterization and evaluation of biochar necessitate specialized analytical techniques designed to examine its interactions with radioactive elements and its resilience under radiation exposure (Devarajan 2024; Fakayode et al. 2024). These methodologies are indispensable in verifying that biochar adheres to the stringent standards of safety, efficiency, and durability required for nuclear applications. Spectroscopic methods, such as X-ray fluorescence (XRF) and gamma spectroscopy, play a pivotal role in identifying the elemental makeup of biochar and in quantifying its capacity to adsorb specific radionuclides (West et al. 2015; Carter et al. 2022). These techniques are instrumental in shedding light on how biochar engages with radioactive materials, aiding in the enhancement of its properties for optimal functionality.

Chromatographic methods, particularly liquid chromatography–mass spectrometry (LC–MS), are utilized to dissect the organic composition of biochar and to scrutinize alterations in its chemical structure following radiation exposure. This form of analysis is vital in gauging the long-term stability of biochar and its potential degradation in radioactive environments (Bonanomi et al. 2023). Radiometric techniques, including alpha and beta counting, are fundamental in directly measuring the radioactivity levels in biochar samples (Daňo et al. 2021). This form of analysis is key in evaluating the proficiency of biochar in adsorbing various radionuclides and in ensuring its alignment with established safety protocols.

Evaluating the durability and stability of biochar in nuclear contexts is essential to ascertain its longevity and efficacy under extended radiation exposure and contact with radioactive materials (Datta et al. 2022). These evaluations encompass a range of tests designed to replicate the conditions biochar would likely face in real-world nuclear environments. Accelerated aging tests are conducted to assess how the properties of biochar evolve when subjected to typical nuclear environmental stressors such as radiation, heat, and chemical agents (Paramasivan 2022). These tests are crucial in forecasting the lifespan of biochar and its sustained effectiveness in nuclear applications.

Thermal stability assessments are critical in determining the capacity of biochar to preserve its structural integrity and adsorption ability at the elevated temperatures encountered in nuclear reactors or waste storage facilities (Palansooriya et al. 2022). These evaluations are imperative to ensure that biochar remains stable and does not release adsorbed radionuclides under thermal duress. Additionally, mechanical strength evaluations, including compression and tensile strength tests, are conducted to gauge the physical robustness of biochar, particularly when employed in structural roles like radiation shielding (Amanu 2022). It is essential to confirm that biochar retains its mechanical properties in nuclear conditions to ensure its reliability and safety in such applications.

7.2 Durability and stability assessments

Evaluating and characterizing biochar for use in nuclear settings, particularly with an emphasis on its durability and stability, is a vital process to confirm its appropriateness and efficacy in these challenging environments (Sutton 2021). This evaluation process is tailored to understand how biochar behaves under the specific conditions encountered in nuclear applications, such as continuous exposure to radiation, extreme temperatures, and interaction with radioactive materials. The endurance of biochar in nuclear environments is gauged through durability assessments. These tests subject biochar to conditions that replicate those found in nuclear contexts, including ongoing radiation exposure and contact with radioactive substances (Szewczak et al. 2020). The objective is to monitor changes in the physical and chemical attributes of biochar over time in these conditions. Key factors under scrutiny include the structural maintenance of biochar, its capacity to adsorb materials, and its overall integrity.

A crucial component of these assessments is examining the stability of biochar when exposed to radiation. Biochar is tested under various levels of ionizing radiation to observe any alterations in its composition or its ability to adsorb materials (Brickler et al. 2021; Ahmed and Hameed 2020). The aim is to verify that biochar can endure typical radiation levels in nuclear environments without substantial deterioration. Testing the thermal stability of biochar is also essential, considering the high temperatures often present in nuclear environments, such as in reactors or waste storage areas (Guilhen et al. 2019; Chen et al. 2021). These tests check if biochar can retain its structural integrity and functionality at high temperatures, a critical factor in determining its reliability for extended use in nuclear applications. Biochar is also subjected to chemical stability assessments, where it is exposed to diverse chemical environments it may encounter in nuclear settings. This includes interaction with radioactive waste, corrosive substances, and various chemical agents. The goal is to ensure that biochar does not engage in harmful chemical reactions that could diminish its effectiveness or safety.

In certain nuclear applications where biochar might be used structurally, such as in radiation shielding, its mechanical strength is tested (Palansooriya et al. 2022; Gupta et al. 2022). This includes evaluating its compressive and tensile strength to ascertain if it can withstand physical stresses and maintain its shape and functionality in nuclear environments. Furthermore, long-term performance evaluations are conducted to gain insight into how biochar performs over prolonged periods in nuclear settings (Mukherjee et al. 2014). This involves examining the potential leaching of adsorbed radionuclides, tracking changes in their adsorption capacity over time, and understanding the overall aging process of biochar.

8 Environmental and economic benefits of biochar in the nuclear sector

8.1 Cost implications and financial benefits

The economic analysis of incorporating biochar into the nuclear region entails an in-depth assessment of its price implications and financial advantages. The manufacturing cost of biochar is prompted using elements consisting of the type of biomass feedstock used, the pyrolysis technique, and the size of manufacturing. Generally, biochar production can be value-effective, especially whilst making use of waste biomass, which no longer most effectively reduces material charges but additionally contributes to waste control solutions.

In phrases of economic blessings, biochar offers numerous benefits inside the nuclear quarter. Its software in radioactive waste control can potentially reduce the prices related to traditional waste remedy methods, which are frequently high-priced and energy-in-depth (Sharma and Reddy 2004). By providing a greater efficient and sustainable technique of radioactive waste adsorption and containment, biochar can lower lengthy-term waste control fees (Guilhen et al. 2019).

Additionally, using biochar in nuclear packages inclusive of radiation defense and reactor performance can cause indirect value financial savings (Mulvaney and Mulvaney 2020). For instance, shielding substances primarily based on biochar, being lighter and potentially extra cost-powerful than conventional materials like lead, can lessen transportation and handling expenses (Natalio et al. 2020). In reactor programs, advanced performance and decreased maintenance wishes can translate into great operational price savings over time.

8.2 Market potential and commercialization strategies

The marketplace capability for biochar inside the nuclear zone is full-size, given the growing emphasis on sustainable and fee-effective answers in nuclear generation. As nuclear strength remains a huge part of the worldwide electricity blend, the call for innovative substances like biochar that could decorate safety, efficiency, and sustainability is probably to grow (Guo et al. 2023b).

Commercialization strategies for biochar within the nuclear area need to be aware of demonstrating its effectiveness and protection through rigorous checking out and certification strategies (Szewczak et al. 2020). Collaborations with nuclear strength groups, research establishments, and regulatory bodies can be essential in establishing biochar as a possible fabric in nuclear packages.

Marketing efforts have to highlight the particular homes of biochar, including its sustainability, performance, and value-effectiveness, to distinguish it from conventional nuclear materials. Targeted advertising in the direction of precise nuclear programs where biochar offers the maximum benefits can facilitate its adoption within the enterprise (Hu et al. 2020). Furthermore, exploring partnerships for big-scale production and delivery chain optimization can help decrease manufacturing expenses and make biochar more competitive in the market. Developing customizable biochar answers tailored to unique nuclear programs also can enhance its market appeal.

8.3 Lifecycle assessment

Life cycle assessment (LCA) of biochar-based remediation focuses on environmental impacts—notably greenhouse gas emissions, energy use, and ecological toxicity—to holistically evaluate sustainability. Particularly in nuclear applications where safety, efficiency, and sustainability are crucial, lifecycle assessment (LCA) is essential in statistically appraising the environmental trade-offs of biochar manufacture, use, and disposal (Gibon and Hahn Menacho 2023). LCA studies typically define the functional unit as the remediation of a given contaminated soil mass or area to safe radiation levels (e.g. per cubic meter or hectare of soil treated) (Lin et al. 2022). The exact specification of the functional unit, which provides a reference by which all inputs and outputs are routinely monitored, is therefore a fundamental beginning point in evaluating these procedures (Zhang et al. 2021; Osman et al. 2024). In biochar-based nuclear waste management, for example, the functional unit could be framed as "the treatment of one cubic meter of radioactive effluent to regulated safety thresholds," so ensuring that all emissions, resource consumption, and environmental impact contextually match an equivalent volume of treated waste (Clayton et al. 2024). Alternatively, should the emphasis be on biochar generation itself, the functional unit might be "1 kg of nuclear-grade biochar," providing a direct link to criteria including feedstock choice, pyrolyzed energy inputs, and post-treatment changes (Carvalho et al. 2022). Whichever definition is selected, it has to faithfully reflect the intended use so that the final evaluation captures actual performance (Guilbot et al. 2013). Across diverse feedstocks and production methods, peer-reviewed LCA results consistently show that using biochar for remediation can yield net environmental benefits. In particular, the stable carbon of biochar contributes to significant climate-change mitigation: one study found that the carbon sequestered in soil by biochar was up to 4.5 times greater than the total greenhouse gases emitted over the life cycle of system. Such negative net emissions mean global warming potential is often greatly reduced relative to conventional cleanup (e.g. excavation or chemical fixation), especially when biochar displaces energy-intensive remediation or landfilling (Alshehri et al. 2023). However, LCAs also highlight trade-offs and potential burdens. The production and deployment of biochar can increase certain impacts: for example, a higher electricity demand for pyrolysis has been linked to greater fossil fuel depletion and even higher life-cycle ionizing radiation impact (due to nuclear energy in the electricity mix).

Some studies report that biochar systems may slightly elevate impacts like particulate matter formation, photochemical ozone creation, acidification, and terrestrial ecotoxicity, largely because of emissions (e.g. NO_x, fine particulates, or trace heavy metals) during feedstock processing and pyrolysis (Osman et al. 2024). Notably, the reduction in pollutant bioavailability achieved by biochar (e.g. fewer heavy metals or radionuclides leaching into ecosystems) is not always fully captured in standard LCA impact metrics, so categories like terrestrial ecotoxicity can remain dominated by upstream emissions rather than remediation benefits (Osman et al. 2024). Despite these nuances, case studies in regions from the Marshall Islands to Fukushima illustrate that applying biochar to radionuclide-contaminated soils can markedly curb Cs-137/Sr-90 uptake by plants and mitigate ecological and food-chain risks (Hamilton et al. 2016).

8.4 Ecological footprint and carbon neutrality

The ecological footprint of nuclear-oriented biochar is another important factor in its sustainability profile. The function of biochar in carbon sequestration is particularly noteworthy (Elkhlifi et al. 2023). When biomass is converted into biochar, a considerable part of its carbon content is stabilized, stopping it from returning to the environment as carbon dioxide. This process correctly makes biochar a technique of carbon sequestration, contributing to carbon neutrality efforts. In nuclear programs, biochar no longer only gives a sustainable answer for waste control and radiation protection but also contributes to reducing the general carbon footprint of nuclear operations (Datta et al. 2022). By changing greater carbon-in-depth materials and approaches, biochar can help make the nuclear industry greater sustainable. Moreover, the ecological footprint of biochar extends beyond carbon sequestration. Its use in environmental remediation, including in treating contaminated water or soil, further complements its ecological blessings. By mitigating pollutants and protecting ecosystems, biochar contributes positively to the general environmental sustainability of nuclear generation (Liu et al. 2024).

9 Regulatory and safety considerations in nuclear biochar applications

9.1 Compliance with nuclear safety standards

The integration of biochar in nuclear applications necessitates strict adherence to nuclear protection requirements and rules. These requirements are designed to ensure the secure handling of radioactive substances, defend workers and the public from radiation publicity, and prevent environmental contamination. Biochar utilized in nuclear settings must meet unique standards regarding its radiological, chemical, and physical homes (Hamilton et al. 2016).

Compliance starts with rigorous testing and certification of biochar to ensure it does now not grow to be a source of secondary contamination. This includes assessing its capability to adsorb and hold radioactive materials without leaching, its structural integrity under radiation publicity, and its thermal stability. Biochar has to be established to preserve its efficacy and stability through the years, specifically in excessive-radiation environments (Li et al. 2020b).

Regulatory bodies, including the Nuclear Regulatory Commission (NRC) in the United States and the International Atomic Energy Agency (IAEA) globally, set tips and requirements for materials utilized in nuclear programs (Rosenthal and Stern 2019; Creager and Rentetzi 2022). Compliance with those requirements calls for ordinary audits, specified documentation of the properties of biochar and dealing with strategies, and adherence to installed safety protocols (Meyer et al. 2017). Manufacturers and users of nuclear-grade biochar need to stay abreast of evolving policies and ensure continuous compliance.

9.2 Handling and disposal protocols

The handling and disposal of biochar in nuclear programs are vital additives to its protection profile. Proper management protocols must be mounted to prevent unintended publicity of radioactive biochar. This includes education for employees in handling techniques, the use of suitable defensive gadgets, and strict control measures to avoid move-contamination. Disposal of spent biochar, especially when it carries adsorbed radioactive materials, is a sizable consideration (Ahmed et al. 2021; Zhuravlev 2019). The disposal method must be selected primarily based on the kind and degree of radioactivity within the biochar, ensuring that it no longer poses any environmental or fitness dangers. Options for disposal include steady landfilling, in which the biochar is isolated toavoid leaching of radionuclides, and incineration in specialized centers able to handle radioactive waste (Das et al. 2023).

In a few cases, recycling or regeneration of biochar may be possible, taking into account its reuse in nuclear applications. However, this must be carefully evaluated to make sure that the regeneration procedure does not diminish its adsorption potential or compromise its protection. Overall, regulatory compliance and secure dealing and disposal protocols are paramount within the use of biochar in nuclear programs (Low et al. 2022; Fawzy et al. 2021). These measures not only ensure the protection and effectiveness of biochar but additionally make contributions to the public's acceptance and recognition of biochar as a possible answer within the nuclear industry. As biochar technology evolves, non-stop engagement with regulatory bodies and adherence to safety requirements may be important in its successful implementation in nuclear programs.

10 Integrating machine learning in biochar-nuclear research

Integrating machine learning (ML) into both biochar and nuclear research represents a promising but still emerging interdisciplinary frontier (An 2024). Figure 7 presents a conceptual diagram outlining the data-driven approach for optimizing biochar in nuclear applications. While direct studies combining these fields are limited, substantial progress has been made independently, showcasing the transformative potential of ML. In biochar research, ML techniques such as ensemble learning, neural networks, and explainable AI have been leveraged to predict biochar yield and properties based on biomass input and pyrolysis parameters, significantly reducing the need for extensive experimentation and improving process efficiency (Nguyen et al. 2024). Models like Random Forest and support vector machines have been integrated with optimization algorithms like genetic algorithms (GA) and particle swarm optimization (PSO) to refine predictions and guide decision-making in biochar synthesis (Haq et al. 2022). ML has also proven useful in evaluating the environmental benefits of biochar, such as its application in tea plantations to mitigate soil acidification and improve crop yield. Key variables such as calcium content and biochar dosage were identified as primary contributors using feature importance analysis within ML models (Yin et al. 2025). Additionally, ML is being employed to model and optimize the use of biochar in water treatment and environmental remediation, offering a cost-effective alternative to traditional pollutant removal methods (Yuan et al. 2023). This includes predicting the adsorption efficiency of biochar for heavy metals and organic contaminants using algorithms like artificial neural networks and random forests, while also considering critical variables like pH, porosity, and surface area (Kumari et al. 2024). In parallel, ML has been advancing nuclear research in significant ways. From surrogate modeling for nuclear accelerators to real-time system diagnostics in reactors, ML is enhancing predictive capabilities and operational safety. For instance, ML has been used to simulate complex interactions in nuclear materials under high radiation and temperature environments, facilitating material discovery and performance prediction (Morgan et al. 2022). Similarly, nuclear fuel characteristics can be predicted using ML techniques such as support vector machines, which are trained on simulated databases to identify key behavioral patterns in irradiated materials (Lu et al. 2023). Furthermore, ML models have demonstrated success in predicting nuclear reactor behavior during abnormal scenarios, aiding in accident identification and decision-making (Fernandez et al. 2017). At a broader level, ML has been integrated into nuclear physics research to explore fundamental properties and generate predictive models for nuclear structure and reactions (Boehnlein et al. 2022). While the two domains currently evolve in parallel, opportunities exist to cross-pollinate insights—for example, applying ML-driven material optimization from nuclear science to engineer advanced biochar materials, or leveraging nuclear diagnostic ML tools to monitor industrial biochar systems. As ML continues to mature across both fields, the future holds strong potential for a unified framework that supports sustainable energy, environmental remediation, and advanced materials research.

11 Conclusions, challenges, and prospects in biochar-based nuclear applications

The application of biochar in nuclear science faces several technical challenges, including variability in biochar properties due to different biomass feedstocks and pyrolysis conditions. This inconsistency can impact its performance in critical areas such as radioactive waste adsorption and radiation protection (Montanarella and Lugato 2013; Mohammadi et al. 2020). Scalability from laboratory to commercial production poses another challenge, with the need to maintain the high quality and specific properties of biochar at a larger scale (Thengane et al. 2021). Moreover, the long-term stability and durability of biochar under nuclear conditions, including radiation exposure and thermal stress, require further research and development (Wang et al. 2020).

Public perception and acceptance are crucial for the adoption of biochar in nuclear science. Concerns about safety and environmental impacts need to be addressed through transparent communication and educational

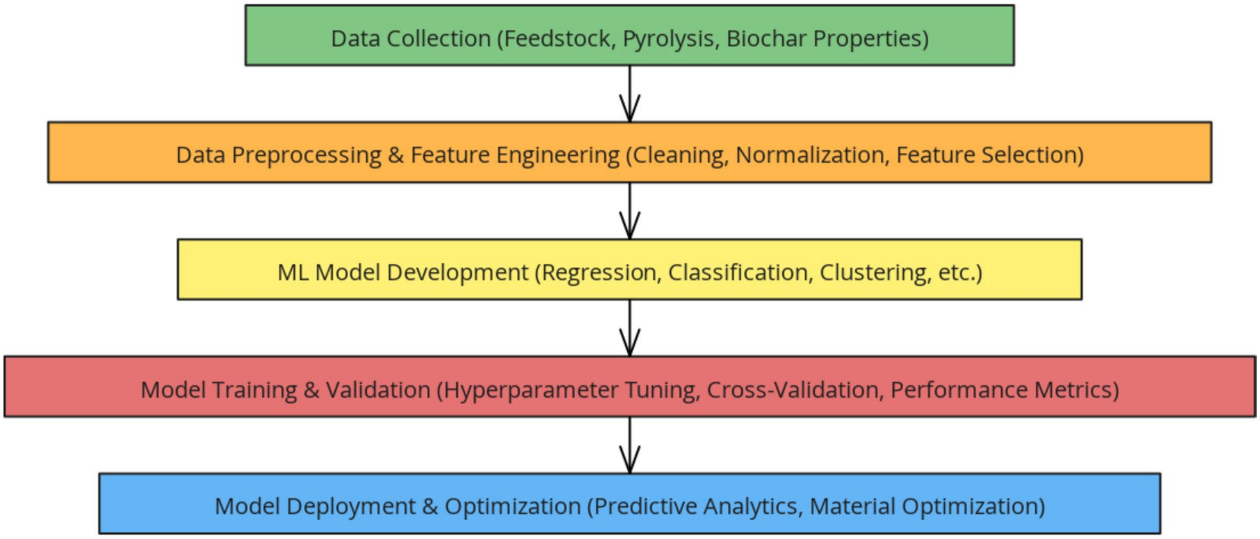


Fig. 7 Conceptual diagram showing how ML guides biochar-nuclear research

efforts. Collaborations with academic institutions and industry experts are vital for disseminating accurate and balanced information about the role of biochar in nuclear safety and sustainability (Alaboudi 2020). Misconceptions about biochar and nuclear technology must be clarified to build trust and acceptance among the public, policymakers, and stakeholders.

The future of biochar in the nuclear era is being shaped through emerging research areas, each promising to amplify its applications and effectiveness. Engineered biochars with enhanced properties for specific nuclear applications are a significant focus. These developments involve manipulating biochar at the molecular level to improve adsorption capacity, thermal stability, and radiation resistance. Recent studies, such as the work by Yan et al. (2020), explore the latest research progress and future trends in biochar applications, underscoring the potential for in-depth research in this field (Yan et al. 2020).

Additionally, the integration of biochar with nanotechnology signifies a promising avenue. Nanoscale modifications could lead to significant efficiency improvements, particularly in adsorbing specific radionuclides. This approach aligns with the emerging trends in biochar composites, as discussed by recent reviews, which classify novel biochar composites and highlight future directions in composite applications (Wang et al. 2017, 2022a).

Hybrid materials, where biochar is combined with other substances such as metal oxides or polymers, are also under exploration. These composites could offer enhanced performance in nuclear applications, such as improved mechanical strength or adsorption selectivity for specific isotopes. The collaborative efforts in biochar research projects, as noted by Celignis, point towards biomass valorization and the potential for future advancements in this area (Celignis 2024).

Breakthroughs in biochar technology for nuclear applications are on the horizon, including the development of biochar-based smart materials that adapt their properties in response to environmental stimuli. This concept is supported by the novel biochar production techniques reviewed by Yaashikaa et al. (2020), which emphasize the importance of biochar in toxic pollutant remediation and its advantages (Yaashikaa et al. 2020). The application of AI and machine learning in biochar research is poised to accelerate the discovery of advanced formulations and manufacturing techniques, leading to more effective solutions for nuclear applications. Moreover, advancements in biochar recycling and regeneration, crucial for enhancing its sustainability and economic viability, are anticipated.

The exploration of biochar in nuclear science and technology has unveiled a multitude of opportunities and benefits. Key insights gathered from this exploration include the exceptional adsorption capacity of biochar for radioactive contaminants, its potential in radiation shielding, and its role in enhancing nuclear reactor efficiency. The versatility of biochar, derived from its tunable physical and chemical properties, makes it a promising candidate for various nuclear applications, from waste management to safety enhancements.

Biochar contributes significantly to the benefits of remediating nuclear waste, which are profound: protecting human health by reducing exposure to harmful radiation, safeguarding ecosystems from contamination, and ensuring the long-term sustainability of nuclear energy. By offering cost-effective and environmentally friendly solutions for immobilizing radionuclides and preventing their dispersion in the environment, biochar addresses critical environmental and safety challenges in the nuclear sector.

Economic evaluations of the integration of biochar into the nuclear industry have highlighted its potential for cost-effectiveness and market viability, especially when compared to conventional nuclear materials and methods. Environmental assessments have underscored the contribution of biochar to sustainability, particularly through carbon sequestration and the reduction of ecological footprints in nuclear operations.

Addressing technical challenges, such as production scalability and consistency, along with regulatory compliance and public perception, is critical for the successful integration of biochar in nuclear applications. The incorporation of advanced technologies like artificial intelligence (AI) and machine learning accelerates research and material optimization, paving the way for more efficient and targeted applications in nuclear technology.

Looking ahead, the vision for biochar in nuclear science and technology is continuous growth and innovation. Future developments are expected to expand the applications of biochar, potentially revolutionizing areas such as nuclear reactor design, radiation therapy in medicine, and space exploration. Biochar is anticipated to evolve from a supplementary material to a key component in the advancement of sustainable nuclear technologies.

The ongoing research and development in biochar technology, particularly in enhancing its properties and overcoming current obstacles, are predicted to open new avenues for its application. The integration of biochar with emerging technologies, including nanotechnology and smart materials, is expected to yield groundbreaking results, further solidifying its role within the nuclear field. In the broader context, the alignment of biochar with global sustainability goals and its contribution to a more environmentally responsible approach to nuclear technology mark a significant shift in how nuclear science is perceived and implemented.

The continued collaboration among researchers, industry experts, policymakers, and the public is critical for realizing the full potential of biochar in this discipline. In conclusion, the journey of biochar in nuclear science and technology is just beginning. Its capacity to contribute to safer, more efficient, and sustainable nuclear applications is substantial. As research continues to advance and innovations emerge, biochar is poised to play a pivotal role in shaping the future of nuclear science and technology, aligning it more closely with the principles of sustainability and environmental stewardship.

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