Sustainability, biochar, waste management, and application possibilities

Biochar, a carbon-rich material derived from the thermal decomposition of organic biomass under low-oxygen conditions, has gained attention as a multifaceted solution for sustainability challenges. Its production and application address critical issues such as waste management, climate change mitigation, soil degradation, and environmental pollution [1]. By transforming organic waste into a stable, valuable resource, biochar supports a circular economy, reducing environmental harm while offering practical benefits across agriculture, remediation, and energy sectors. Its versatility stems from its tunable properties, which depend on feedstock and production methods, making it a promising tool for sustainable development [2].

One of biochar's most significant contributions to sustainability is its role in waste management. Globally, organic waste—such as agricultural residues, food scraps, forestry byproducts, and sewage sludge—accounts for a substantial portion of municipal and industrial waste streams. When sent to landfills, this waste decomposes anaerobically, releasing methane, a greenhouse gas with a warming potential 25 times greater than carbon dioxide. Open burning of crop residues, another common practice, emits carbon dioxide, black carbon, and particulate matter, contributing to air pollution and health risks. Biochar production offers an alternative by converting these waste streams into a stable product through processes like pyrolysis. For instance, rice husks, corn stover, or yard trimmings can be pyrolyzed to produce biochar, diverting waste from landfills and reducing emissions. This process stabilizes carbon in a form that resists microbial degradation for centuries, effectively sequestering it and mitigating climate change. Estimates suggest that widespread biochar use could offset up to 1 gigaton of carbon dioxide emissions annually by 2050, depending on production scale and feedstock availability [3-6].

In agriculture, biochar enhances sustainability by improving soil health and reducing reliance on resource-intensive inputs. Its porous structure increases soil water retention, particularly in sandy or degraded soil, reducing irrigation needs—a critical benefit in water-scarce regions. Biochar also enhances nutrient retention, binding ions like ammonium and phosphate, which minimizes fertilizer runoff and prevents eutrophication in nearby water bodies. Studies have shown that biochar amendments can boost crop yields by 10–20% in nutrient-poor soils, particularly in tropical climates. Additionally, biochar fosters beneficial microbial communities, which improve nutrient cycling and soil resilience [7]. By reducing the need for synthetic fertilizers, biochar lowers the carbon footprint of agriculture, as fertilizer production is energy-intensive and emits nitrous oxide, another potent greenhouse gas.

Biochar's environmental remediation potential further underscores its sustainability benefits. Its high surface area and diverse functional groups enable it to absorb contaminants, including heavy metals (e.g., lead, cadmium) and organic pollutants (e.g., pesticides, dyes). In contaminated soils, biochar

This research was supported by the Science Fund of the Republic of Serbia, # 10810
Sustainable solutions in environmental chemistry: exploring biochar potential–EnviroChar

Ovaj dokument je sačinjen uz finansijsku podršku Fonda za nauku Republike Srbije. Za sadržinu ove publikacije isključivo je odgovoran Univerzitet u Novom Sadu Prirodno-matematički fakultet i ta sadržina ne izražava stavove Fonda za nauku Republike Srbije

immobilizes metals, reducing their bioavailability and preventing uptake by plants or leaching into groundwater [8-10]. For example, biochar derived from wood residues have been shown to reduce lead mobility in soil by up to 70%. In wastewater treatment, biochar filters can remove organic pollutants, offering a low-cost alternative to activated carbon. These properties make biochar a valuable tool for restoring polluted sites, such as former industrial zones or mine tailings, where conventional remediation is costly and invasive. However, biochar's effectiveness depends on its properties, which vary with feedstock and production conditions. For instance, biochar from manure may contain high ash and nutrient content, enhancing soil fertility but potentially introducing salts or contaminants if not properly processed [11].

Beyond agriculture and remediation, biochar has applications in energy and industry. During pyrolysis, volatile gases and bio-oils are released, which can be captured and used as biofuels or feedstocks for chemical production. This improves the energy efficiency of biochar production and reduces reliance on fossil fuels. Biochar itself can serve as a renewable fuel in certain contexts or as a component in advanced materials, such as carbon electrodes for batteries or catalysts in industrial processes. These applications highlight biochar's role in diversifying resource streams and supporting a transition to a low-carbon economy [12].

Despite its promise, challenges remain in scaling up biochar production and ensuring its environmental safety. Energy requirements for pyrolysis can offset carbon benefits if non-renewable sources are used, and large-scale production demands significant infrastructure investment. Variability in biochar properties complicates standardization, as biochar from contaminated feedstocks (e.g., sewage sludge) may introduce pollutants like heavy metals or polycyclic aromatic hydrocarbons (PAHs) into soil. Regulatory frameworks are needed to establish quality standards, ensuring biochar is safe and effective for its intended use. Additionally, economic barriers, such as high initial costs for pyrolysis units, may limit adoption, particularly in developing regions where waste management needs are greatest [13].

To overcome these hurdles, localized production systems could enhance sustainability. Community-based pyrolysis units, powered by renewable energy, could process local waste streams like crop residues or municipal green waste, minimizing transportation emissions and creating jobs. Research into low-cost, modular reactors is also advancing, making biochar production more accessible. Policymakers can support adoption through incentives, such as carbon credits for sequestration or subsidies for farmers using biochar. Education and outreach are equally critical to ensure end-users understand biochar's benefits and application methods, avoiding misuse that could diminish its effectiveness.

In conclusion, biochar represents a transformative approach to sustainable waste management and resource utilization. By converting organic waste into a stable, multifunctional material, it addresses interconnected challenges—climate change, soil degradation, pollution, and resource scarcity. While scalability and standardization remain hurdles, biochar's ability to sequester carbon, enhance

This research was supported by the Science Fund of the Republic of Serbia, # 10810
Sustainable solutions in environmental chemistry: exploring biochar potential–EnviroChar

Ovaj dokument je sačinjen uz finansijsku podršku Fonda za nauku Republike Srbije. Za sadržinu ove publikacije isključivo je odgovoran Univerzitet u Novom Sadu Prirodno-matematički fakultet i ta sadržina ne izražava stavove Fonda za nauku Republike Srbije

agriculture, remediate environments, and support renewable energy makes it a cornerstone of regenerative practices. With strategic implementation, biochar can play a pivotal role in building a resilient, sustainable future.

References:

1. Shyam, S., Ahmed, S., Joshi, S.J. *Sarma, H.* Biochar as a Soil amendment: implications for soil health, carbon sequestration, and climate resilience. *Discov. Soil* **2025***,* 2, 18. https://doi.org/10.1007/s44378-025-00041-8.
2. Mujtaba, M., Fraceto, L.F., Fazeli, M., Mukherjee, S., Savassa, S.M., de Medeiros, G.A., Santo Pereira, A.E., Mancini, S.D., Lipponen, J., Vilaplana, F. Lignocellulosic biomass from agricultural waste to the circular economy: a review with focus on biofuels, biocomposites and bioplastics, *Journal of Cleaner Production* **2023**, 402,136815. https://doi.org/10.1016/j.jclepro.2023.136815.
3. Amalina, F., Krishnan, S., Zularisam, A.W., Nasrullah, M. An extensive analysis and environmental sustainability applications of multifunctional biochar developments: Current trends and technological advances, *Green Technologies and Sustainability* **2025**, 3(3), 100174. https://doi.org/10.1016/j.grets.2025.100174.
4. Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., Iqbal, R. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. https://doi.org/10.3390/su13031330
5. Lakhouit, A. Mitigating landfill emissions strategies for effective waste management in tabuk, *Cleaner Waste Systems* **2024**, 9, 100187. https://doi.org/10.1016/j.clwas.2024.100187.
6. International Biochar Initiative. *State of the Biochar Industry Report* **2025**. **https://biochar-international.org/state-of-the-biochar-industry-2015/**
7. Bano, A., Aziz, M.K., Prasad, B., Ravi, R., Shah, M.P., Dos Santos Lins, P.V., Meili, L., Prasad, K.S. The multifaceted power of biochar: A review on its role in pollution control, sustainable agriculture, and circular economy, *Environmental Chemistry and Ecotoxicology* **2025**, 7, 286-304. https://doi.org/10.1016/j.enceco.2025.01.004.
8. Nosratabad, A.N., Yan, Q., Cai, Z., Wan, C. Exploring nanomaterial-modified biochar for environmental remediation applications. *Heliyon* **2024,** *10*(18), e37123. https://doi.org/10.1016/j.heliyon.2024.e37123
9. Olugbenga, O.S., Adeleye, P.G., Oladipupo, S.B., Adeleye, A.T., John, K.I. Biomass-derived biochar in wastewater treatment- a circular economy approach, *Waste Management Bulletin* **2024***,* 1, 4, 1-14. https://doi.org/10.1016/j.wmb.2023.07.007.
10. Beljin, J., Đukanović, N., Anojčić, J., Simetić, T., Apostolović, T., Mutić, S., Maletić, S. Biochar in the Remediation of Organic Pollutants in Water: A Review of Polycyclic Aromatic Hydrocarbon and Pesticide Removal. *Nanomaterials* **2025**, *15*, 26. https://doi.org/10.3390/nano15010026
11. Trivedi, Y., Sharma, M., Mishra, R.K., Sharma, A., Joshi, J., Gupta, A.B., Achintya, B., Shah, K., Vuppaladadiyamd, A.K. Biochar potential for pollutant removal during wastewater treatment: A comprehensive review of separation mechanisms, technological integration, and process analysis, *Desalination* **2025**, 600, 118509. https://doi.org/10.1016/j.desal.2024.118509.
12. Santos, D.C.B.D., Evaristo, R.B.W., Dutra, R.C., Suarez, P.A.Z., Silveira, E.A., Ghesti, G.F. Advancing Biochar Applications: A Review of Production Processes, Analytical Methods, Decision Criteria, and Pathways for Scalability and Certification. *Sustainability* **2025**, *17*, 2685. https://doi.org/10.3390/su17062685.
13. Anokye, K. From waste to wealth: Exploring biochar's potential in energy generation and waste mitigation, *Cleaner and Circular Bioeconomy* **2024**, 9, 100101. https://doi.org/10.1016/j.clcb.2024.100101

This research was supported by the Science Fund of the Republic of Serbia, # 10810
Sustainable solutions in environmental chemistry: exploring biochar potential–EnviroChar

Ovaj dokument je sačinjen uz finansijsku podršku Fonda za nauku Republike Srbije. Za sadržinu ove publikacije isključivo je odgovoran Univerzitet u Novom Sadu Prirodno-matematički fakultet i ta sadržina ne izražava stavove Fonda za nauku Republike Srbije