Biochar – a Step Towards Sustainable Crop Production in the Republic of Croatia

Biougljen – korak prema održivoj biljnoj proizvodnji u Republici Hrvatskoj

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BIOCHAR – A STEP TOWARDS SUSTAINABLE CROP PRODUCTION IN THE REPUBLIC OF CROATIA

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SUMMARY

Modern agricultural production faces significant challenges including soil degradation, climate change and rising costs within production systems. Biochar, a carbon-rich material obtained by pyrolysis of organic waste biomass, is emerging as one of a series of steps towards sustainable crop production. This review paper analyses the basic physicochemical properties of biochar and its role as a soil conditioner, with an emphasis on its ability to increase water holding capacity, cation exchange capacity (CEC) and to regulate soil reaction, especially on degraded soils. Beyond agronomic benefits, biochar serves as a "Negative Emission Technology" by sequestering carbon for centuries and mitigating greenhouse gas emissions. In the Republic of Croatia, research focuses on acid soils and valorizing viticultural residues. Innovative applications, such as foliar biochar sprays for grapevines and the use of sewage-sludge-derived biochar for heavy metal adsorption, demonstrate its versatility. While biochar acts more as a long-term soil amendment than an immediate corrective agent, its integration into Croatian agroecosystems follows a science-based pathway; however, the adoption of biochar-based products is still not at a high level.

Keywords: soil amendment, sustainable agriculture, carbon sequestration, GHG mitigation, foliar biochar sprays

INTRODUCTION

Modern agriculture increasingly faces severe soil degradation caused by intensive agricultural practices and mismanagement of land resources, while natural processes such as climate change and extreme weather events further exacerbate these impacts (Wang et al., 2026). The anthropogenic character of soil and land degradation is primarily caused by incorrect selection of agronomic practices as well as by ignoring or only partially following crop production recommendations, such as not adhering to fertilization guidelines, which gradually decreases soil nutrient content and soil organic matter (Jug et al., 2022; Bogunovic et al., 2023; Kabir et al., 2023). Addressing agricultural soil degradation is complex and requires a scientifically grounded and innovative approach that considers the specifics of the agro-ecological production area. Intensive crop production can negatively affect the environment and soil health, which may ultimately result in food of lower quality (Khan et al., 2024). Global demand for food continues to grow, and given climate change, rising input costs, and increasing environmental awareness among consumers, food production has become highly demanding and requires rapid responses from farmers to newly emerging challenges (Jug et al., 2022).

The global scientific community is paying significant attention to sustainable crop production systems, aiming to identify soil amendments that can improve various aspects of agricultural production including economic, ecological, sociological, and agronomic factors (Ajibade et al., 2022). One such soil amendment that currently attracts considerable scientific interest both in the European Union and worldwide is biochar. Biochar is a material produced by heating biomass, which after processing contains between 65% and 95% carbon. Several thermochemical production processes are currently known, most of which are based on pyrolysis - an efficient, economical, and energy-effective method of

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producing charcoal (Đurđević et al., 2017; Khan et al., 2024).

According to numerous research studies, biochar can increase soil fertility and quality through several key mechanisms: raising the pH of acidic soils, increasing soil water-holding capacity, increasing humus content, stimulating beneficial soil microorganisms, improving the soil cation-exchange capacity (CEC), and retaining nutrients within the root zone (Đurđević et al., 2017; Khan et al., 2024). In addition, biochar offers a major advantage: its application contributes to carbon sequestration, because biochar is highly resistant to microbial decomposition and mineralization and can persist in soil for up to a thousand years (Kabir et al., 2023). Considering the wide range of biochar's beneficial effects, and the fact that many agricultural soils in Croatia frequently face limiting factors such as low pH, poor aeration and water regime, low soil organic matter, and low nutrient concentrations, it is highly important to scientifically determine and evaluate the effects of biochar on low-fertility soils. Recent field experiments conducted in Croatia have demonstrated that biochar application significantly reduces soil bulk density and improves soil structure in Stagnosols; however, the available evidence is still largely limited to short-term local experiments (Đurđević et al., 2017; Bogunovic et al., 2023).

Such knowledge may ultimately improve crop yield potential and enhance the economic viability of sustainable agricultural production in the Republic of Croatia. The aim of this review paper is to provide an overview of current knowledge regarding biochar production and application, with particular emphasis on the Republic of Croatia. The paper summarizes the historical development and modern technologies of biochar production, its physicochemical and biological properties, and its effects on soil processes and crop production. Additionally, it discusses the opportunities and challenges associated with biochar use in Croatian agroecosystems, including its potential role in improving soil fertility, enhancing carbon sequestration, and supporting sustainable agricultural development (Đurđević et al., 2017). A better understanding of biochar's functions and benefits may contribute to the development of science-based recommendations for its application and to the long-term sustainability and economic viability of agricultural production in the Republic of Croatia.

BIOCHAR PRODUCTION PROCESS

Biochar production has been known and applied for thousands of years and is now scientifically well established. Biochar is currently produced by thermochemical conversion of biomass under conditions of limited or no oxygen, most often through the pyrolysis process (Tripathi et al., 2016; Lehmann and Joseph, 2024). Pyrolysis is often carried out in simple, technologically modest furnaces (traditional charcoal production) that have been used since ancient times and are still widespread globally. Such systems release significant amounts of heat and environmentally harmful gases directly into the atmosphere, which makes them economically inefficient and potentially harmful to the environment (Sparrevik et al., 2013).

The basic principle when choosing a feedstock is that the biomass should be a residue or waste material that is not intended for human or animal consumption (Lehmann and Joseph, 2024; EBC, 2024). Since the properties of biochar depend largely on the origin of the feedstock and the production conditions, scientific validation of biochar performance requires long-term experimental trials and research on different soil types, climatic conditions and management systems – especially when the goal is to achieve lasting changes in soil organic carbon content, nutrient cycling and soil structure improvement (Woolf et al., 2010; Jeffery et al., 2017).

In contrast, modern biochar production systems are designed as fully-closed or semi-closed systems with improved thermal integration and emission control, which allows for the simultaneous recovery of energy (heat and/or electricity) along with biochar production (Meyer et al., 2011; IBI, 2023). These production systems significantly affect the yield, structural properties, and functional efficiency of biochar.

The most commonly used methods include slow pyrolysis, medium or fast pyrolysis, hydrothermal carbonization (HTC), and torrefaction. Each of these techniques requires a specific range of temperature, heating rate, and residence time, which ultimately determines the composition, stability, and other important properties of the final product (Danesh et al., 2025). Slow pyrolysis is considered the most commonly used and most efficient method for producing high-quality biochar. It is produced under conditions of limited access to oxygen, with the process of thermal decomposition of biomass at temperatures ranging from approximately 400 to 750 °C. During slow pyrolysis, biomass is gradually carbonized, resulting in three basic product fractions: solid - biochar, liquid - bio-oil, and non-condensable gases (pyro gases). The yield of these products strongly depends on process parameters such as the type of biomass, heating rate, temperature, particle size, and reactor configuration. Slower heating and longer process times produce solid fractions because it starts secondary reactions that stabilize carbon in the solid matrix. Under optimized conditions, approximately 50 % of the initial carbon from the biomass can then be preserved in biochar (Lee et al., 2017).

Another important thermochemical process is hydrothermal carbonization (HTC), which uses wet biomass and transforms it into a carbon-rich material known as hydrochar. The main difference from pyrolysis is that HTC takes place in a medium with higher water content (75–90%) at elevated pressure and relatively moderate temperatures, typically between 180 and 280 °C. This is a main advantage of the process as it does not require energy-intensive drying (Khan et al., 2019). The process results in two main products: hydrocarbons (liquid phase containing dissolved organic compounds) and a small amount of gaseous products (dominantly carbon dioxide). Hydrocarbons may have a relatively high calorific value and potential use as solid fuels; they typically have a lower carbon content, lower specific surface area, and lower pore volume than biochar produced by pyrolysis at higher temperatures and with dry biomass (Ighalo et al., 2025).

Torrefaction is a thermochemical pretreatment that occurs at temperatures between approximately 200 and 300°C in a weakly oxidizing atmosphere. During torrefaction, thermal decomposition of the biomass occurs, removing moisture and volatile components (pyro gases). The resulting material is characterized by increased energy value, greater hydrophobicity, and a better grinding structure, which facilitates storage, transport, and further processing (Kota et al., 2022). Mentioned properties, of course, depending on the biomass and usually the final product has limited porosity and a lower specific surface area compared to fully carbonized biochar, which limits its application in environmental remediation (Bukhsh et al., 2025).

In general, the choice of the appropriate biochar production method depends on the properties of the feedstock and the intended application of the final product. Among the available technologies, slow pyrolysis is the most widespread and is still considered the most efficient approach to obtain structurally stable, carbon-rich biochar with increased porosity and satisfactory chemical properties. These properties are key.

BIOCHAR – FROM BLACK TO GREEN

Biochar is increasingly regarded as a link between sustainable agriculture, waste biomass management, and renewable energy production (Bhattacharyya et al., 2024). During pyrolysis, volatile organic compounds released from biomass can be captured and used for energy production, while the solid carbon-rich fraction can be returned to the soil as a soil amendment (Asadi et al., 2021). This approach supports circular-economy principles by recycling organic residues and improving soil quality simultaneously (Khan et al., 2024). The main characteristics of biochar are high aromaticity, structural stability, large specific surface area, microporosity, and the presence of functional groups on the surface (Rizwan et al., 2023). These physicochemical properties give biochar high adsorption (electrochemical binding to internal and external surfaces) and absorption (retaining water, air, and dissolved nutrients within the pores). Due to its surface charges and porous structure, biochar can be described as an "electrochemical sponge" within the soil (Đurđević et al., 2017).

A high percentage of agricultural areas around the world, including soils in Croatia, have suffered significant losses of soil organic carbon (SOC) as a result of intensive agricultural production, removal of crop residues, and insufficient input of organic matter (Bogunović et al., 2023). It is estimated that some soils have lost between 25 % and 75 % of their original organic carbon content (Lal, 2004; Đurđević et al., 2019). Such a degradation process negatively affects soil structure, water holding capacity, biological activity, and overall soil suitability and its productivity. In this context, biochar represents a promising amendment for restoring and stabilizing soil organic carbon, increasing soil resilience, and improving the soil sustainability for crop production (Bhattacharyya et al., 2024).

Organic carbon stabilization and accumulation in soils is crucial for their functionality. However, conventional agricultural systems often exhibit a negative carbon balance due to biomass removal, crop residue burning, bioenergy production, overgrazing, and erosion (Asadi et al., 2021). Continued carbon export without adequate compensation has led to widespread soil degradation, with biologically active soils being converted into structurally and functionally degraded substrates. Restoring and stabilizing carbon in soil is therefore a critical objective of sustainable land management. Biochar production and application in soil provide a promising pathway for long-term carbon stabilization and functional soil enhancement (Figure 1) (Gross et al., 2021; Afshar and Mofatteh, 2024).

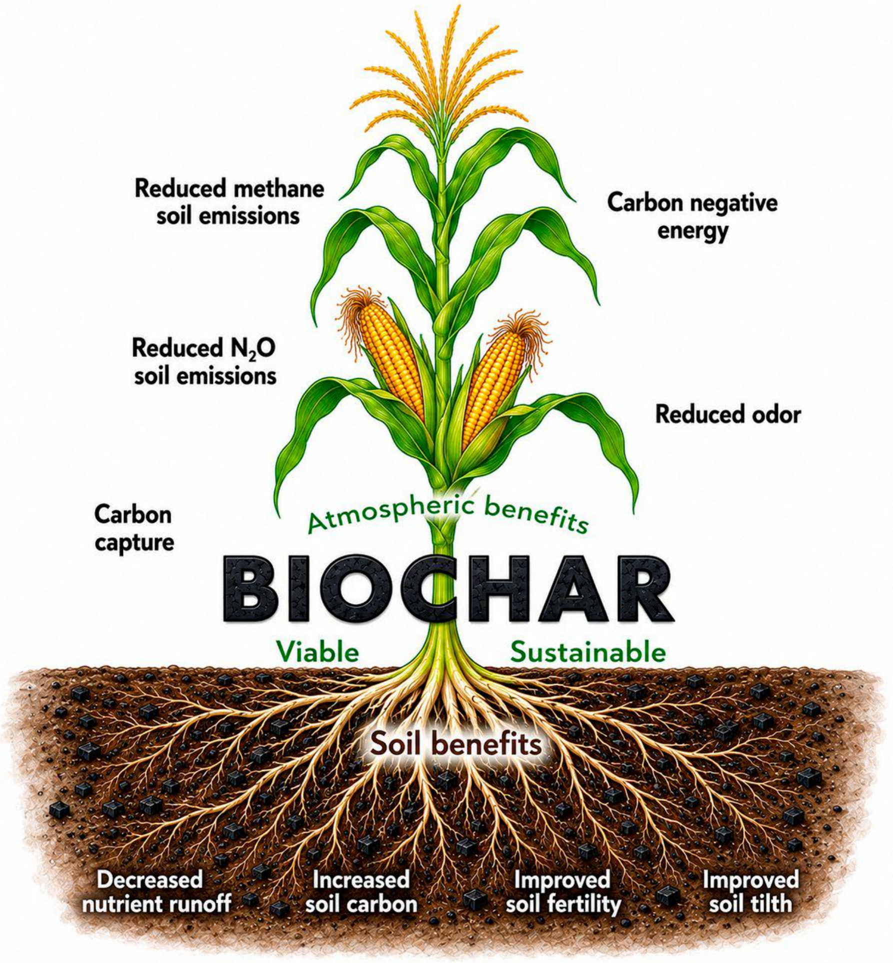

Figure 1. The main benefits of biochar in the soil and atmosphere.
Slika 1. Glavne prednosti biougljena u tlu i atmosferi.

EFFECTS ON SOIL CHEMICAL, PHYSICAL, AND BIOLOGICAL PROPERTIES

The application of biochar as a soil conditioner has been widely reported to enhance key soil quality indicators, including physical, chemical, and biological properties. In both agronomic and climate-policy contexts, biochar fulfils a dual role: (i) improving soil functionality and resilience, and (ii) contributing to climate change mitigation through long-term carbon sequestration (Woolf et al., 2010; Lehmann et al., 2021)

Owing to its highly porous structure and large specific surface area, biochar significantly modifies soil physical architecture. Biochar improves soil physical properties through multiple interacting mechanisms (Blanco-Canqui, 2017). These include an increase in total pore volume due to the intrinsic porosity of biochar particles, formation of interfacial pore spaces between biochar and surrounding soil aggregates, enhanced aggregate stability, increased pore persistence and structural resilience, reduction in bulk density, and thus lower compaction risk, improvement in macro- to micropore ratios, optimizing water–air balance. The effectiveness of biochar as a water-regulating amendment is therefore texture-dependent. In sandy soils, biochar reduces percolation rates and enhances plant-available water while in clayey soils, biochar may improve infiltration and aeration by reducing excessive water stagnation.

Biochar applications often increase field water capacity, particularly at higher application rates, resulting in improved plant growth and drought resilience. In conditions of limited precipitation or prolonged drought, soils amended with biochar show enhanced water-use efficiency and increased plant tolerance to water stress.

Biochar significantly affects soil chemical properties through modifications in soil reaction (pH), cation exchange capacity (CEC), soil organic matter content, electrical conductivity (EC), and nutrient availability. Biochar can affect soil pH through two main phases. Short-term phase: After the first application, due to microbial decomposition, it comes to the release of CO_2 and small amounts of organic acids, which occasionally leads to a temporary decrease in pH. Long-term phase:

Biochar generally has an alkalizing and buffering effect, especially in acidic soils, due to its ash content, the presence of carbonates and functional groups on the surface of char (Đurđević et al., 2018; Lehmann et al., 2021). The liming effect (ameliorative) of biochar can indirectly affect the processes of denitrification and nitrogen transformation in the soil. Biochar generally acts as a pH buffer, reducing natural soil pH fluctuations and mitigating anthropogenic acidification effects such as those caused by nitrogen fertilization.

One of the most important chemical properties of biochar is its ability to increase the cation exchange capacity (CEC) and base saturation. The pyrolysis process increases the specific surface area and charge density, which increases the negative surface charge. This increase in CEC of the soil reduces nutrient leaching, especially in sandy soils, and improves the retention of cations such as Ca^{2+}, Mg^{2+}, K^+ and NH_4^+. Increasing the CEC also depends on the pH value, as the deprotonation of functional groups raises the charge density. Biochar also has high impact on increase of the total organic matter content of the soil and promotes the proportion of dissolved organic carbon (DOC) (Dai et al., 2025). The mobility of DOC depends on the clay content, the presence of Fe/Al oxides, soil pH, molecular weight and morphological properties of the soil. Increased pH can increase the deprotonation of functional groups in DOC, thereby increasing solubility and affecting carbon cycling and sequestration processes (Dai et al., 2025).

Biochar stimulates the development of agriculturally important soil microorganisms and positively affects their enzymatic activity. As biochar is very porous, its pores provide suitable places for the development of numerous microorganisms, protecting them and providing necessary nutrients. The intensity and direction of the impact of biochar on the biological properties of the soil are strongly determined by climate, fertilization method, crop rotation, and the initial composition of the microbial community in the soil. The overall effect of biochar varies depending on the soil type and physicochemical properties. The most positive effects in the recent research are most often observed in soils with low fertility and unfavorable physicochemical properties (Đurđević et al., 2018).

BIOCHAR AND CLIMATE CHANGE

Anthropogenic activities - including industrial production, fossil fuel combustion, energy production, and agriculture - are among the emitters that have increased concentrations of major greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere.

The accumulation of these gases increases the greenhouse effect, by which longwave radiation emitted from the surface of the Earth is partially trapped and then re-radiated back towards the surface, leading to additional warming of the atmosphere and terrestrial systems (IPCC, 2021).

Although agriculture contributes approximately 10–12% of global CO_2 emissions, its contribution to CH_4 and N_2O emissions is significantly higher. Through enteric fermentation, manure management, and nitrogen fertilization, agriculture accounts for roughly 40% of global methane emissions and up to 60–70% of anthropogenic nitrous oxide emissions (IPCC, 2022).

Recent research indicates that biochar application can contribute to the mitigation of all three major greenhouse gases: CO_2, through long-term carbon sequestration in stable aromatic structures; N_2O, through altered nitrification–denitrification pathways and improved nitrogen retention; CH_4, through improved soil aeration and modification of microbial communities (Woolf et al., 2010; Lehmann et al., 2021).

According to modelling studies, transitioning from conventional biomass disposal (e.g., burning or uncontrolled decomposition) to controlled pyrolysis and biochar production could reduce global CO_2-C emissions by up to 1.5–2.0 Gt per year. This represents approximately 10–12 % of current anthropogenic CO_2 emissions. Over the century, cumulative mitigation potential may exceed 100 Gt CO_2-C, depending on biomass availability and sustainable source limitations (Woolf et al., 2010).

The potential of biochar to mitigate climate change is based in its classification as a negative emission technology (NET). A portion of the biomass of carbon is converted into stable biochar during pyrolysis, while volatile fractions may be used for bioenergy production, but also, when biochar is applied to soil, a substantial proportion of carbon can be stabilized for decades to centuries.

Even if bioenergy produced during pyrolysis is subsequently combusted, the net carbon balance remains negative because more carbon is stabilized in soil than is being re-emitted during energy recovery (Lehmann et al., 2021).

At the moment, three primary biomass-based energy strategies are being discussed globally (Figure 2):

1. Conventional Biomass Combustion (Carbon-Neutral Model)

The system assumes carbon neutrality, based on the premise that plants absorb CO_2 during growth and release it upon burning or decomposition. In idealized frameworks, biogenic CO_2 emissions are treated as climate-neutral (IPCC, 2022). However, this assumption strongly depends on time scales, land-use change effects, and sustainable sources of biomass (Searchinger et al., 2018). Large-scale biomass removal raises concern about food and energy competition, loss in biodiversity, and long-term decline in soil fertility due to organic matter depletion and nutrient export (Creutzig et al., 2015; Smith et al., 2016). Also, soil carbon stocks may decline if harvest residues are excessively removed without compensation, particularly in intensively managed agroecosystems (Lal, 2015).

2. Bioenergy with Carbon Capture and Storage (BECCS)

This system uses biomass primarily for energy production, with the emitted CO_2 captured and permanently stored in geological formations. This system is presented as a negative emission technology in climate mitigation scenarios, which can limit global warming to 1.5–2 °C (Fuss et al., 2018; IPCC, 2022). BECCS offers theoretical net-negative emissions; there are major uncertainties regarding the sustainable supply of biomass, infrastructure requirements, public acceptance, and long-term storage capacity and safety (Creutzig et al., 2015; Smith et al., 2016). Implementation of this system would require significant areas of land, potentially putting pressure on ecosystems and land resources (Searchinger et al., 2018).

3. Biochar-Based Pyrolysis Systems

Combining the production of biochar for use as a soil amendment with energy generation (heat, syngas, bio-oil) is the most value-added process as it sequesters carbon in soil while simultaneously producing clean energy. In comparison with direct combustion, total usable energy output may be lower, but pyrolysis systems achieve carbon stabilization and, in that form, carbon can remain in soils for decades to centuries (Woolf et al., 2010; Lehmann et al., 2021). This approach uniquely combines renewable energy production with carbon sequestration, while also enhancing soil fertility, improving nutrient retention, and increasing agricultural resilience (Lal, 2015; Jeffery et al., 2017).

Life cycle assessments show that biochar systems can achieve net-negative emissions while providing agronomic co-benefits, especially when residues or waste biomass are used as feedstock (Woolf et al., 2010). Hence, biochar systems represent a multifunctional solution for climate and soil rather than an exclusively energy-focused technology, integrating mitigation, adaptation, and soil restoration objectives within the framework of a circular bioeconomy (Lal, 2004; Lehmann et al., 2021).

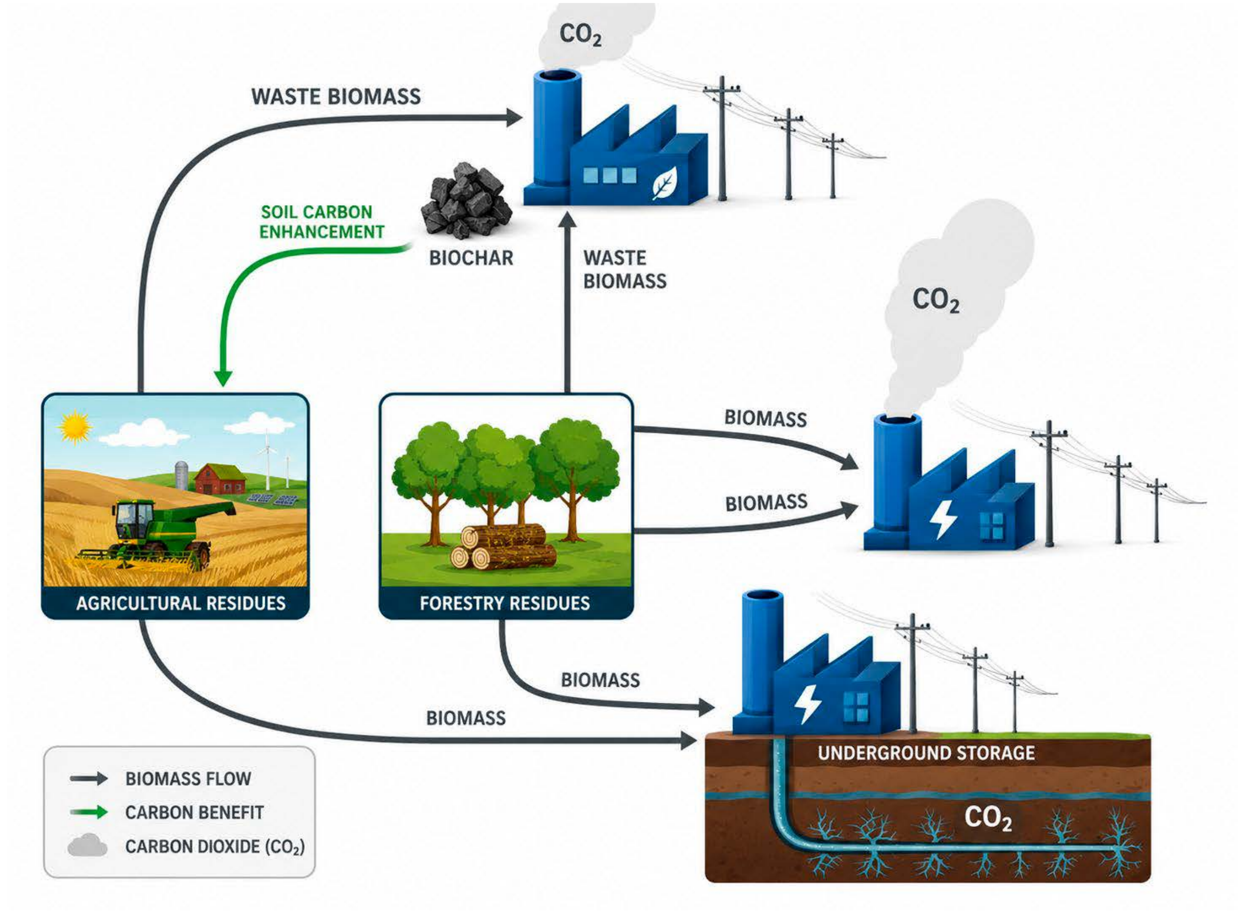

Figure 2. Primary biomass-based energy strategies.

Slika 2. Primarne energetske strategije zasnovane na biomasi.

BIOCHAR IN THE REPUBLIC OF CROATIA

Biochar research in the Republic of Croatia has developed primarily along two complementary trajectories. The first is agricultural and soil science applications focusing on the remediation of acidic and structurally sensitive soils characteristic of continental regions. The second is environmental engineering, where biochar is evaluated as a cost-effective material for removal of pollutants from aqueous and waste streams. Croatia also possesses significant biomass potential, especially from vineyard residues such as vineyard prunings, which positions biochar as a key component of circular bioeconomy strategies within the national agro-industrial sector (Bogunovic et al., 2023; Cvitan et al., 2026). A key agronomic challenge in this regard is managing soil acidity to maintain productivity, where comparative field studies assess the effectiveness of biochar versus traditional sugar factory waste lime. Evidence suggests that although liming allows for a faster and more pronounced increase in soil pH, biochar acts as a long-term soil conditioner rather than an immediate corrective agent (Đurđević et al., 2018). Therefore, in the Croatian context biochar is viewed as a soil restoration material, not only as a liming material. This approach is particularly evident in the management of stagnosols, which are highly prevalent in continental Croatia and are extremely sensitive to compaction and excessive periodic waterlogging (both above and below ground) and are very challenging soils when it comes to improving soil physicochemical conditions. Current research examines the combined effect of different tillage systems and organic amendments, with results indicating that biochar is most effective when applied as part of an integrated system adapted to local pedological and climatic conditions (Bogunović et al., 2023).

To assess the impact of biochar and mineral fertilization on weediness and yield of winter wheat, Brozović et al. (2021) conducted a field experiment in Croatia on two soil types, gleysol and stagnosol. The results showed that the application of biochar, especially in combination with nitrogen fertilization, affects weed occurrence and, depending on the soil properties, can contribute to increased wheat yields.

In addition to traditional incorporation into the soil, one research direction in Croatia includes the foliar application of biochar as an aqueous suspension on the indigenous grape variety Malvasia Istriana. This innovative approach uses biochar as an amendment that can positively affect the composition of both grapes and wine (Palčić et al., 2025; Prelac et al., 2025). To ensure the effectiveness of such applications, research was conducted on locally collected biomass used for biochar production, establishing the basis for assessing the biochar quality in the research area (Cvitan et al., 2026). In addition to its application in agronomy, research in Croatia also includes the evaluation of thermochemical conversion of sewage sludge into biochar with the aim of promoting a circular economy, i.e., the utilization of potentially hazardous waste materials that are difficult to manage. Research has shown that biochar obtained by pyrolysis of sewage sludge is an effective adsorbent for the removal of heavy metals such as Cd, Cr, Cu, and Pb from wastewater (Nakić et al., 2025a). This dual approach, which simultaneously addresses waste management and pollution control, is an increasingly significant area of interest in scientific and economic circles (Nakić et al., 2025b).

A review of the scientific literature to date confirms that biochar research in Croatia is characterized by specific environmental goals, a transition towards sustainable plant production with the remediation of degraded and polluted soils, and a diversification of application methods - from foliar application in viticulture to the sorption of heavy metals in wastewater treatment (Bogunović et al., 2023; Nakić et al., 2025a; Cvitan et al., 2026).

CONCLUSION

Biochar can serve as a crucial link between waste management, climate change mitigation, and soil health. It can also facilitate the transition towards sustainable agriculture. Controlled pyrolysis of waste biomass enables the production of quality biochar, which can enable farmers to increase soil organic carbon, significantly improve nutrient retention, and increase drought resistance due to improved soil porosity.

In the Republic of Croatia, the strategic use of biochar is currently focused mainly on addressing local challenges, such as soil acidity and structural degradation of stagnosols, where it contributes to the restoration of degraded soils. However, Croatia lacks long-term field trials that could help introduce biochar to farmers. Its adoption will also depend on the coordination of all stakeholders, particularly the implementation of appropriate policy interventions related to biochar carbon sequestration potential, with strict adherence to quality control standards (such as EBC). Biochar acts primarily as a long-term soil improver, and should never be presented as a quick corrective soil conditioner. Its integration into Croatian agricultural production should be based on a scientifically based approach that supports environmental protection and the long-term economic sustainability of national agricultural production.

REFERENCES

1. Afshar, M., & Mofatteh, S. (2024). Biochar for a sustainable future: Environmentally friendly production and diverse applications. *Results in Engineering*, *23*, 102433. https://doi.org/10.1016/j.rineng.2024.102433
2. Ajibade, S., Nnadozie, E. C., Iwai, C. B., Ghotekar, S., Chang, S. W., Ravindran, B., & Kumar Awasthi, M. (2022). Biochar-based compost: a bibliometric and visualization analysis. *Bioengineered*, *13*(7-12), 15013-15032. https://doi.org/10.1080/21655979.2023.2177369
3. Asadi, H., Ghorbani, M., Rezaei-Rashti, M., Abrishamkesh, S., Amirahmadi, E., Chengrong, C. H. E. N., & Gorji, M. (2021). Application of rice husk biochar for achieving sustainable agriculture and environment. *Rice Science*, *28*(4), 325-343. https://doi.org/10.1016/j.rsci.2021.05.004
4. Bhattacharyya, P. N., Sandilya, S. P., Sarma, B., Pandey, A. K., Dutta, J., Mahanta, K., Lesueur, D., Nath, B. C., Borah, D., & Borgohain, D. J. (2024). Biochar as soil amendment in climate-smart agriculture: opportunities, future prospects, and challenges. *Journal of Soil*

Science and Plant Nutrition, *24*(1), 135-158. https://doi.org/10.1007/s42729-024-01629-9

5. Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal*, *81*(4), 687-711. https://doi.org/10.2136/sssaj2017.01.0017
6. Bogunovic, I., Dugan, I., Pereira, P., Filipovic, V., Filipovic, L., Krevh, V., Defterdarovic, J., Matisic, M., & Kisic, I. (2023). Effects of biochar and cattle manure under different tillage management on soil properties and crop growth in Croatia. *Agriculture*, *13*(11), 2128. https://doi.org/10.3390/agriculture13112128
7. Brozović, B., Jug, I., Jug, D., Stipešević, B., Ravlić, M., & Đurđević, B. (2021). Biochar and Fertilization Effects on Weed Incidence in Winter Wheat. *Agronomy*, *11*(10), 2028. https://doi.org/10.3390/agronomy11102028
8. Bukhsh, K., Chen, C., Su, G., Dong, S., Li, L., Deng, S., Li, X., Ma, J., & Wang, X. (2025). Comparative advantages of biomass-derived biochars via torrefaction under flue gas and nitrogen atmosphere. *Journal of Analytical and Applied Pyrolysis*, *190*, 107120. https://doi.org/10.1016/j.jaap.2025.107120
9. Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S., & Masera, O. (2015). Bioenergy and climate change mitigation: an assessment. *Gcb Bioenergy*, *7*(5), 916-944. https://doi.org/10.1111/gcbb.12205
10. Cvitan, D., Anđelini, D., Prelac, M., Javed, Q., Užila, Z., Pasković, I., Major, N., Černe, M., Goreta Ban, S., Bubola, M., Jeromel, A., Karažija, T., Petek, M., Nemet, I., & Palčić, I. (2026). Physicochemical Properties of Biochar Produced from Grapevine-Pruning Residues of 12 Cult ivars. *Horticulturae*, *12*(1), 4. https://doi.org/10.3390/horticulturae12010004
11. Dai, W., Bao, Z., Meng, J., Chen, T., & Liang, X. (2025). Biochar makes soil organic carbon more labile, but its carbon sequestration potential remains large in an alternate wetting and drying paddy ecosystem. Agronomy, 15(7), 1547. https://doi.org/10.3390/agronomy15071547
12. Danesh, P., Prussi, M., Salimbeni, A., Negro, V., & Chiaramonti, D. (2025). Review on Biochar Upgrading Methods for Its Application in Thermochemical Conversion Processes and Critical Materials Recovery. *Sustainability*, *17*(22), 10194. https://doi.org/10.3390/su172210194
13. Đurđević, B., Jug, I., Jug, D., Vukadinović, V., Stipešević, B., & Brozović, B. (2017). Primjena biougljena kao kondicionera tla–korak ka održivoj biljnoj proizvodnji.
14. Đurđević, B., Jug, I., Vukadinović, V., Brozović, B., Stipešević, B., Bogunović, I., Šeremešić, S., & Jug, D. (2018). Effects of biochar and sugar factory lime application on soil reaction in acidic soils. *Agriculturae Conspectus Scientificus*, *83*(1), 31-37.
15. Đurđević, B., Jug, I., Jug, D., Bogunović, I., Vukadinović, V., Stipešević, B., & Brozović, B. (2019). Spatial variability of soil organic matter content in Eastern Croatia assessed using different interpolation methods. *International Agrophysics*, *33*(1). https://doi.org/10.31545/intagr/104372
16. EBC (European Biochar Certificate). (2024). *European Biochar Certificate – Guidelines for a sustainable production of biochar*. Retrieved from https://www.european-biochar.org
17. Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente-Vicente, J. L., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental research letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f
18. Gross, A., Bromm, T., & Glaser, B. (2021). Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy*, *11*(12), 2474. https://doi.org/10.3390/agronomy11122474
19. IBI (International Biochar Initiative). (2023). *Standardized product definition and product testing guidelines for biochar*. Retrieved from https://biochar-international.org
20. Ighalo, J. O., Akaeme, F. C., Georgin, J., de Oliveira, J. S., & Franco, D. S. P. (2025). Biomass Hydrochar: A Critical Review of Process Chemistry, Synthesis Methodology, and Applications. *Sustainability*, *17*(4), 1660. https://doi.org/10.3390/su17041660
21. IPCC (International Panel on Climate Change). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from https://dx.doi.org/10.1017/9781009157896
22. IPCC (International Panel on Climate Change). (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from https://dx.doi.org/10.1017/9781009157926
23. Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, *12*(5), 053001. https://doi.org/10.1088/1748-9326/aa67bd
24. Jug, I., Jug, D., Brozović, B., Vukadinović, V., & Đurđević, B. (2022). Osnove tloznanstva i biljne proizvodnje.
25. Kabir, E., Kim, K. H., & Kwon, E. E. (2023). Biochar as a tool for the improvement of soil and environment. *Frontiers in Environmental Science*, *11*, 1324533. https://doi.org/10.3389/fenvs.2023.1324533
26. Khan, T. A., Saud, A. S., Jamari, S. S., Ab Rahim, M. H., Park, J. W., & Kim, H. J. (2019). Hydrothermal carbonization of lignocellulosic biomass for carbon rich material preparation: A review. *Biomass and Bioenergy*, *130*, 105384. https://doi.org/10.1016/j.biombioe.2019.105384
27. Khan, S., Irshad, S., Mehmood, K., Hasnain, Z., Nawaz, M., Rais, A., Gul, S., Wahid, M. A., Hashem, A., Abd_Allah, E. F., & Ibrar, D. (2024). Biochar Production and Characteristics, Its Impacts on Soil Health, Crop Production, and Yield Enhancement: A Review. *Plants*, *13*(2), 166. https://doi.org/10.3390/plants13020166
28. Kota, K. B., Shenbagaraj, S., Sharma, P. K., Sharma, A. K., Ghodke, P. K., & Chen, W. H. (2022). Biomass torrefaction: An overview of process and technology assessment based on global readiness level. *Fuel*, *324*, 124663. https://doi.org/10.1016/j.fuel.2022.124663

29. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *science*, *304*(5677), 1623-1627. https://doi.org/10.1126/science.1097396
30. Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, *7*(5), 5875-5895. https://doi.org/10.3390/su7055875
31. Lee, J., Kim, K. H., & Kwon, E. E. (2017). Biochar as a Catalyst. *Renewable and Sustainable Energy Reviews*, *77*, 70-79. https://doi.org/10.1016/j.rser.2017.04.002.
32. Lehmann, J., & Joseph, S. (Eds.). (2024). *Biochar for environmental management: science, technology and implementation*. Taylor & Francis. https://doi.org/10.4324/9781003297673
33. Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela M. E., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, *14*(12), 883-892. https://doi.org/10.1038/s41561-021-00852-8
34. Meyer, S., Glaser, B., & Quicker, P. (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. *Environmental science & technology*, *45*(22), 9473-9483. https://doi.org/10.1021/es201792c
35. Nakić, D., Posavčić, H., Licht, K., & Vouk, D. (2025a). Application of novel biochar derived from experimental sewage sludge gasification as an adsorbent for heavy metals removal. *Sustainability*, *17*(3), 997. https://doi.org/10.3390/su17030997
36. Nakić, D., Posavčić, H., Matošević, D., & Tomaš, I. (2025b). Perspectives on the application of biochar produced from sewage sludge gasification in wastewater treatment for heavy metals removal. *Environmental Engineering-Inženjerstvo okoliša*, *12*(1-2), 26-34. https://doi.org/10.37023/ee.12.1-2.3.
37. Palčić, I., Anđelini, D., Prelac, M., Pasković, I., Černe, M., Major, N., Ban, S. G., Užila, Z., Bubola, M., Ban, D., Nemet, I., Karažija, T., Petek, M., Korenika, A. M. J., & Cvitan, D. (2025). Influence of Biochar foliar application on Malvazija Istarska grapevine physiology. *Sustainability*, *17*(13), 5947. https://doi.org/10.3390/su17135947
38. Prelac, M., Anđelini, D., Cvitan, D., Užila, Z., Major, N., Kovačević, T. K., Ban, S. G., Ban, D., Plavša, T., Damijanić, K., & Palčić, I. (2025). Foliar Application of Biochar-Based Suspensions: Effects on Composition and Sensory Properties of Malvazija istarska (Vitis vinifera L.) Must and Wine. *Sustainability*, *18*(1), 364. https://doi.org/10.3390/su18010364
39. Rizwan, M., Murtaza, G., Zulfiqar, F., Moosa, A., Iqbal, R., Ahmed, Z., Irshad, S., Khan, I., Li, T., Chen, J., Zhang, M., Siddique, K. H., Leng, L., & Li, H. (2023). Sustainable manufacture and application of biochar to improve soil properties and remediate soil contaminated with organic impurities: a systematic review. *Frontiers in Environmental Science*, *11*, 1277240. https://doi.org/10.3389/fenvs.2023.1277240
40. Searchinger, T. D., Beringer, T., Holtsmark, B., Kammen, D. M., Lambin, E. F., Lucht, W., Raven, P., & van Ypersele, J. P. (2018). Europe's renewable energy directive poised to harm global forests. *Nature communications*, *9*(1), 3741. https://doi.org/10.1038/s41467-018-06175-4.
41. Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., & Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature climate change*, *6*(1), 42-50. https://doi.org/10.1038/NCLIMATE2870
42. Sparrevik, M., Field, J. L., Martinsen, V., Breedveld, G. D., & Cornelissen, G. (2013). Life cycle assessment to evaluate the environmental impact of biochar implementation in conservation agriculture in Zambia. *Environmental science & technology*, *47*(3), 1206-1215. https://doi.org/10.1021/es302720k
43. Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and sustainable energy reviews*, *55*, 467-481. https://doi.org/10.1016/j.rser.2015.10.122
44. Wang, H., Zeng, H., Wang, Q., Zhou, R., Xu, Z., Fan, M., Al-Farga, A. M., & Zhou, Q. (2026). Global agro-environmental trends and challenges. Agricultural Environment and Sustainability, 1(1), 100006. https://doi.org/10.1016/j.ages.2025.100006
45. Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature communications*, *1*(1), 56. https://doi.org/10.1038/ncomms1053

BIOUGLJEN – KORAK PREMA ODRŽIVOJ BILJNOJ PROIZVODNJI U REPUBLICI HRVATSKOJ

SAŽETAK

Suvremena poljoprivreda suočava se s brojnim izazovima, uključujući degradaciju tla, klimatske promjene i rast troškova proizvodnje. Biougljen, kao materijal bogat ugljikom dobiven pirolizom otpadne organske biomase, sve se više ističe kao korak koji povezuje implementaciju održive biljne proizvodnje. U ovome radu analiziraju se fizikalno-kemijska svojstva biougljena te njegova uloga kao poboljšivača tla koji može unaprijediti kapacitet tla za vodu, kationski izmjenjivački kapacitet (KIK) te utjecati na reakciju tla, osobito u degradiranim tlima. Osim agronomskih koristi, biougljen djeluje i kao tehnologija smanjenja koncentracije stakleničkih plinova u domeni klimatskih promjena jer omogućuje dugotrajnu sekvestraciju ugljika. U Republici Hrvatskoj istraživanja su ponajprije usmjerena na kisela tla te primjenu u vinogradarskoj proizvodnji. Inovativne primjene, poput folijarne primjene biougljena na vinovoj lozi te uporabe biougljena dobivenoga iz mulja otpadnih voda za adsorpciju teških metala, ukazuju na njegovu široku primjenjivost. Iako biougljen djeluje prvenstveno kao dugoročan poboljšivač tla, a ne kao sredstvo za brzu korekciju, njegova integracija u hrvatske agroekosustave temelji se na znanstvenome pristupu; međutim, primjena proizvoda na bazi biougljena još uvijek nije na zadovoljavajućoj razini.

Ključne riječi: poboljšivač tla, održiva poljoprivreda, sekvestracija ugljika, ublažavanje emisija stakleničkih plinova, folijarna primjena biougljena

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