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CHARCOAL AND BIOCHAR RESEARCH IN SERBIA

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ABSTRACT

Charcoal and biochar, two carbon-rich products derived from the pyrolysis of biomass, are the subject of renewed scientific interest due to their diverse roles in archaeology, agriculture, environmental protection and industry. This review provides a comprehensive synthesis of Serbian research conducted between 2004 and 2024, highlighting the diversity of biomass sources, pyrolysis conditions and the expanding range of applications for these materials. Charcoal, traditionally used as a fuel, is explored here in its broader role – from archaeological analyses revealing ancient human-environment interactions to modern applications in radon monitoring, organic agriculture, detoxification by adsorption, and medicine. In particular, retorted beech charcoal has proved very useful in improving soil fertility and developing antimicrobial composites. In parallel, biochar research in Serbia has focused on the production of wood and non-wood biomass, including agricultural residues and invasive plant species, with applications spanning soil improvement, environmental remediation, pollutant adsorption, enzyme immobilization, and bioenergy. This review highlights the interdisciplinary importance of charcoal and biochar, their evolving production methods, and their untapped potential for environmental, agricultural, and technological progress in Serbia and beyond.

Keywords: charcoal, biochar, archaeology, adsorption, agriculture, industry

INTRODUCTION

Society's demand for energy from sustainable sources in order to decrease use of fossil fuels and address climate changes has led to investigations into alternative processes. Biomass pyrolysis is a thermochemical process that decomposes organic material at high temperatures in the absence of oxygen. In this manner, valuable products are obtained: carbon-rich solids, bio-oil, and syngas. While wood was traditionally the primary feedstock, a broader variety of raw materials is now used. The additional benefit of a wider range of source materials is the reduction of organic waste in landfills, better waste management, and the promotion of circular economy practices. To ensure the sustainability of biomass pyrolysis, it is essential to optimize process efficiency, minimize emissions, and source feedstock in a way that avoids competition with food production or contributes to deforestation.

Depending on the biomass and pyrolysis conditions, two major carbon-rich solids can be obtained: charcoal and biochar. These materials, which differ significantly in terms of production parameters, physical characteristics, and applications, are primarily used for environmental purposes, such as soil enhancement and carbon sequestration. The highly porous structure of biochars enables better soil water retention, nutrient availability, and microbial activity and is used in agricultural applications. Charcoal, however, is often produced at higher temperatures and has a denser structure in comparison to biochar. It is usually used for heating in both traditional and industrial settings.

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Charcoal and biochar beyond their traditional uses present an interesting topic for researchers. The research efforts of Serbian scientists to expand on raw materials, correlate pyrolysis parameters with properties of resulting products, and widen applications are presented. In Serbia, charcoal enjoys significant attention for its diverse applications, from environmental monitoring to agricultural practices. Charcoal, particularly activated forms such as retorted beech charcoal, is used for measuring radon concentration, enhancing agricultural yields, and even offering potential therapeutic benefits in medical treatments.

This review presents the efforts of Serbian researchers: to diversify the range of biomass feedstocks used in pyrolysis, including various forms of agricultural and forestry waste; to investigate the relationships between pyrolysis parameters and the physical and chemical properties of the resulting carbonaceous materials; and to explore and broaden the applications of both biochar and charcoal beyond their traditional uses, with particular emphasis on their potential in environmental monitoring, agriculture, and medicine.

CHARCOAL

This review applies a systematic methodology to examine the Serbian scientific literature on charcoal published between 2004 and 2024. Sources were identified through Kobson, SCIndeks, Google Scholar, and DOI-linked Serbian academic journals. Keywords used in both Serbian and English included terms such as *charcoal*, *ćumur*, *activated charcoal*, and *wood carbonization*. Only peer-reviewed publications that focused primarily on charcoal were included; sources with only passing mentions were excluded. The inclusion criteria were: (i) publications published between 2004 and 2024; (ii) peer-reviewed articles, scientific reports, or academic books; (iii) literature focused substantially or exclusively on charcoal (e.g., in terms of production, application, analysis, or historical context); (iv) studies conducted within Serbia or by Serbian authors on relevant domestic topics. After screening approximately 84 records, 26 relevant publications were selected based on clearly defined inclusion criteria. The majority of the publications primarily addressed charcoal found at various archaeological sites (11) and its use as an energy source or in industrial contexts (8). Fewer studies explored the application of charcoal for adsorption (2), agriculture (2), medicine (1), and in determining radon concentrations (2).

Charcoal in archaeology

Charcoal analysis in Serbian archaeology provides important insights into the environment, resource utilization, and human adaptation from the Mesolithic to the Iron Age. The charcoal analysis at Vlašac sheds light on Mesolithic firewood selection and its possible ritual significance. The study identified 20 taxa from 661 charcoal fragments, with *Cornus*, *Quercus* (deciduous oak), and *Prunus* dominating (20–30%). The burn pit contained Prunus and Quercus charcoal, but no *Cornus* charcoal, although it contained abundant Cornelian cherry fruit seeds, suggesting deliberate selection. This suggests that the cornelian cherry may have had a symbolic meaning in funerary rituals. The results highlight the selectivity of humans in the use of firewood, possibly related to environmental availability and cultural practices (Allué et al., 2011). The charcoal found in the Vlašac fire pits shows various Mesolithic-Neolithic burial practices. Burnt human remains, calcified bones and charred artefacts indicate ritual cremations (Borić et al., 2009; 2014). Investigations in Vinca (Filipović et al., 2017) illustrate the management of forest resources and the limited human influence on the vegetation. Neolithic settlements in the Danube and Morava Plain (Marinova et al., 2013) show charcoal as evidence of the utilization of wild plants and the local composition of forests. Excavations at Iron Age sites in south-east Serbia (Filipović et al., 2017) also document plant and charcoal remains that provide information about land use and agricultural practices. Wood is preserved over long periods, primarily in the form of charcoal. On the basis of charcoal analyses, Medović (2021) assume that mainly Moesian beech was used in the construction of the Viminacium amphitheatre during the Roman period. The presence of charcoal was observed in lime mortars from the Roman period, indicating a strategic choice of materials and the reutilisation of resources (Nikolić et al., 2023). Mrgić (2010) investigated forest resources in medieval Serbia and Bosnia and identified different groups of trees that were favoured for certain activities and products. For example, *gvozd* and *gora* (lat. – *mons*, *silva*), which refer to a mountain

Table 1. Charcoal use in Serbian archaeology: chronology, function, and taxa
Tabela 1. Wykorzystanie węgla drzewnego w archeologii serbskiej: chronologia, funkcja i taksony

Time Period	Archaeological sites/sources	Main findings/interpretation	Dominant taxa/ Charcoal use
Paleolithic	Velika Pećina (Stiner et al., 2022)	Evidence of climatic adaptation via fire use	Not specified
Mesolithic	Vlašac (Allué et al., 2011; Borić et al., 2009; 2014)	Selective firewood use, symbolic funerary rituals; cremation pits	*Cornus, Quercus, Prunus*
Neolithic	Vinca (Filipović and Obradović, 2013); Danube & Morava Plains (Marinova et al., 2013)	Woodland management, plant use, low anthropogenic vegetation impact	Local wild species; woodland composition
Iron Age	SE Serbia (Filipović et al., 2016)	Land use, agriculture, plant/charcoal remains	Not specified
Roman Period	Viminacium (Medović et al., 2021); Roman mortars (Nikolić et al., 2023)	Beech used in construction; charcoal in lime mortar implies resource recycling	*Fagus moesiaca* (Moesian beech)
Medieval Period	Serbia & Bosnia (Mrgić, 2010)	Forest terminology; different tree groups for pitch, timber, and charcoal production	Dense forests; unspecified taxa based on activity type

covered with dense, mature forests, were primarily used for timber, pitch, and the production of charcoal. In addition, charcoal finds from the Palaeolithic site of Velika Pećina (Stiner et al., 2022) provide evidence of human adaptation to climatic shifts. Over the millennia, the charcoal remains show the development of the sustainability of settlements, burial customs, and environmental interactions in the Balkans.

To summarize the archaeological evidence discussed above, Table 1 provides a chronological summary of the archaeological evidence for the use of charcoal in Serbian archaeology, as described above. The table highlights key sites, interpreted functions of charcoal, and the dominant plant taxa identified through analysis. This visual summary illustrates the evolving role of charcoal in relation to environmental conditions, cultural practices, and resource management from the Paleolithic to the medieval period.

As shown, the table supports a comparative understanding of how charcoal use evolved across archaeological contexts in Serbia.

Role of Charcoal in Serbia's Fuel and Industrial Applications

Charcoal production in Serbia is an important but often overlooked sector that provides an income for many rural households. Despite its economic and social importance, the industry remains largely unregulated, lacking modern production methods and market support. Various types of charcoal kilns are used, including traditional earth-covered kilns, brick kilns, portable steel kilns, and more advanced retorts (Glavonjić et al., 2011). However, the sector is underdeveloped and receives little attention from policymakers or industry leaders, limiting its potential for growth and efficiency improvements.

The utilization of wood biomass as an energy source has a long tradition in Serbia, but still operates inefficiently. Every year, more than 3.5 million cubic metres of wood are harvested for energy production, much of which is wasted due to outdated processing and combustion methods (Đerčan et al., 2012). Modernizing production could significantly improve efficiency and sustainability. Charcoal in particular offers opportunities for expansion, both for domestic consumption and export markets, but faces challenges such as lack of investment, poor infrastructure and an underdeveloped market. A major problem in charcoal production is the lack of standardized quality control. The European (EN 1860-2), Russian (GOST 7657-84) and Serbian (SRPS.D.B9.020) standards provide guidelines for charcoal and charcoal briquettes, but Serbian producers have problems with certification and market adaptation. Certification schemes such as "DIN-Geprüft" and "DINplus" could help Serbian charcoal to compete in international markets, but further regulatory support and industry adaptation is needed (Petrović and Glavonjić, 2011).

Charcoal also played an important role in Serbian industrial history. In metallurgy, it was an important fuel for the smelting and processing of metals. Archaeological investigations of slag from early iron production sites in eastern Serbia confirm the historical use of charcoal in metal processing. The high iron content in slag samples indicates that early iron metallurgy relied on the combustion of wood and charcoal for the smelting processes (Živković et al., 2005). This historical link emphasizes the long-standing importance of charcoal and its continued relevance for industrial applications.

Apart from its historical importance, the use of charcoal is still widespread in Serbia. Studies on household energy consumption show that solid fuels, including charcoal, firewood and pellets, are a dominant source of heating. While district heating and gas are available in urban areas, a large part of the population relies on wood-based fuels (Glavonjić, 2011). Restaurants and butchers use charcoal for frying; charcoal is also indispensable in blacksmithing and various handicraft businesses. Despite this demand, Serbian charcoal production does not meet the entire market potential, which is due to inefficiencies in production and distribution. Research shows that the total consumption of woody biomass in Serbia in 2010 was 7.41 million m^3, of which 7.03 million m^3 was in the form of roundwood and 0.38 million m^3 in the form of wood waste from industry (Glavonjić and Oblak, 2012). This illustrates the predominance of roundwood in biomass consumption and the need to optimize resource use for greater efficiency. The broader wood biomass industry in Serbia also offers opportunities for improvement. Charcoal is one of the five most commonly used wood fuels in Serbia, along with firewood, briquettes, pellets and woodchips. While households use almost all wood fuels, woodchips are mainly used in industry (Perić et al., 2020). Modernization of the sector, including charcoal production, could reduce environmental impacts while increasing economic benefits. Medium and low technology industries, including wood processing and charcoal production, have a measurable impact on economic performance (Trlaković et al., 2018). Investments in the charcoal sector, together with policy reforms, could improve Serbia's competitiveness in regional and global markets.

This section offers a comparative overview of Serbia's charcoal sector, linking its historical significance in metallurgy and traditional energy use to its ongoing role in household heating, food services, and artisanal production. It also indicates key issues facing the modern sector, such as outdated kiln technologies, a lack of standardized quality control, and limited regulatory or market support. This highlights a significant gap between the country's long-established practices and its untapped potential for industrial modernization and sustainable development.

The Role of Retorted Beech Charcoal in Organic Agriculture

The use of charcoal in agriculture has gained attention due to its potential to increase soil fertility, improve plant growth, and contribute to sustainable organic farming. Recent studies have emphasized the benefits of beech charcoal from the retort, particularly in vegetable and fruit production, where it improves yields and plant development by influencing soil structure and nutrient availability.

A study on organic pepper cultivation shows the positive effects of retorted beech charcoal in combination with cow manure (Živković et al., 2020). The trial was conducted in a greenhouse under controlled conditions and included two treatment groups: one with cow dung alone and one with cow dung supplemented with retorted beech charcoal. The results showed that the pepper plants grown in charcoal-enriched soil had an average yield increase of 27.35% compared to the control group. This significant improvement is attributed to the charcoal's ability to retain moisture and nutrients, creating a more favourable environment for root development and plant growth. Similarly, studies on standard blueberries have shown that retorted beech charcoal promotes shoot growth, an essential factor for plant vigour and fruit production (Živković et al., 2023). In the study, different amounts of charcoal (50 g, 100 g, and 150 g per plant) were compared with a control group grown without charcoal. The results showed a clear correlation between the amount of charcoal and plant development, with the highest application rate (150 g) causing the most significant increase in shoot length and number. Remarkably, the charcoal-treated plants also showed improved growth in the second year of observation, indicating their long-term benefits for soil improvement and plant health. The effectiveness of retorted beech charcoal in agriculture is largely due to its physical and chemical properties. The material, which is produced by controlled carbonization of beech wood, retains a high degree of porosity, allowing it to retain and gradually release water and essential nutrients to the plants. In addition, the alkaline pH (9–11) and the high ash content, which contains potassium, calcium, and magnesium oxides, help to improve soil fertility. The presence of phosphates in the ash additionally supports plant nutrition and makes it an excellent soil additive for organic farming.

The reviewed studies demonstrate that retorted beech charcoal significantly improves plant growth, yield, and long-term soil fertility in organic agriculture, particularly when used in combination with organic fertilizers such as cow manure. This evidence highlights the material's dual agronomic and ecological value, as its unique physical and chemical properties (high porosity, nutrient retention, and alkaline ash composition) position it as a sustainable alternative to conventional soil amendments, bridging traditional organic practices with innovative soil management strategies.

Charcoal for Adsorption: Applications in Health, Food Safety, and Water Treatment

The use of activated charcoal in adsorption processes has attracted considerable attention due to its efficiency in removing various contaminants. In Serbia, the application of locally produced activated charcoal has been studied, especially in terms of the adsorption of toxic substances, including organophosphate (OP) pesticides, mycotoxins, and heavy metals.

Organophosphate poisoning remains a clinical problem, with treatment focusing primarily on decontamination and pharmacological intervention (Vučinić et al., 2018). Activated charcoal plays a crucial role in initial treatment as it prevents further absorption of OP compounds in the event of ingestion. Another critical application of adsorption-based treatment is the removal of deoxynivalenol from food crops. As reported by Jajić et al. (2008), maize and wheat in Serbia exhibit high deoxynivalenol contamination rates; therefore necessitating purification methods. The combination of activated charcoal with alumina and cation exchange resins has demonstrated effective removal of deoxynivalenol, underlining the importance of adsorption technology in food safety. In addition, activated carbon derived from Serbian beech has shown remarkable potential in wastewater treatment.

The integration of Serbian charcoal into adsorption processes is a sustainable approach to environmental and public health challenges. Whether for clinical decontamination, improving food safety or wastewater treatment, the use of locally produced charcoal emphasizes its versatility and effectiveness in mitigating hazardous pollutants.

Charcoal-Based Composite Systems in Medicine

Activated charcoal has shown great promise in medicine, particularly in the development of composite systems for targeted therapeutic applications. One such system combines activated charcoal with zinc alginate hydrogel to combat antimicrobial resistance and support cancer treatment. This composite platform releases bioactive agents like zinc ions and iodine, which are adsorbed onto the charcoal particles. Upon contact with physiological fluids, these active ingredients are released simultaneously and enable local treatment of malignant wounds and cancerous tissues (Osmokrović et al., 2024). The antimicrobial properties of the composite have been extensively tested against multi-resistant strains of bacteria and yeast, all isolated from patient wounds. The combination of zinc ions and iodine showed strong antibacterial and antifungal effects, particularly in combating resistant strains, which are a growing problem in clinical settings. In addition, the zinc ions showed cytotoxic activity against cancer cell lines, including those for metastatic breast cancer and malignant melanoma, indicating their potential in cancer treatment (Osmokrović et al., 2024).

Charcoal Canisters in Radon Monitoring: Insights from Niska Banja Spa and Gabrovnica Area

Radon exposure, especially in areas with naturally high radon levels, poses a significant health risk. Two studies conducted in Serbia focus on monitoring radon concentrations using charcoal canisters, a simple but effective tool for monitoring indoor and outdoor radon.

In the first study, Niska Banja, a health resort known for the therapeutic use of radon, was analysed for its elevated radon levels. Using charcoal canisters and measuring devices, the radon was measured in the thermal pools, the therapy rooms and the surrounding areas. The results showed dangerously high radon concentrations, particularly near the thermal pools, and raised concerns for the health of medical staff due to prolonged exposure (Nikolov et al., 2012). In the second study, charcoal containers were again used to determine the radon levels in the vicinity of the former uranium mine in Gabrovnica, eastern Serbia. Increased radon activity both in the soil and in indoor air was noted in the nearby village of Kalna. Charcoal containers were placed in eight flats in Kalna for 48 hours to measure the radon concentration. The radon adsorbed on the charcoal grains decayed into secondary products such as ^{214}Pb and ^{214}Bi, which were detected by gamma spectroscopy (Nikolov et al., 2014). These studies emphasize the crucial role of charcoal canisters in radon monitoring, as they provide a practical and easily accessible method for assessing radon concentrations, particularly in regions with persistent environmental problems associated with past industrial activities.

Toward an Integrated Understanding of Charcoal Use in Serbia

The diverse findings discussed in the previous sections are synthesized in a comparative summary. Table 2 presents a structured overview of the various applications of charcoal, based on Serbian literature published between 2004 and 2024, highlighting key parameters such as domain, purpose, and main findings.

This comparative table highlights the interdisciplinary scope of charcoal research in Serbia over the past two decades. While archaeological and fuel-related studies dominate in volume, emerging research into agriculture, medicine, and environmental monitoring signals a diversification of focus areas. The findings reveal not only historical and industrial relevance but also innovative potential in sustainable development, public health, and climate-resilient agriculture.

BIOCHAR

In the scientific literature, several terms are used to describe the solid products obtained from the pyrolysis of biomass, aside from charcoal (Serbian: ćumur, ћумур). These include biochar (Serbian: biočađ, биочађ), char (Serbian: čađ, чађ), and hydrochar (Serbian: hidročađ, хидрочађ). Biochar refers to a solid product similar to charcoal, produced through the pyrolysis of biomass in a total or partial absence of oxygen. Char is a solid product derived from the thermal decomposition of any organic material, while hydrochar is formed from biomass via hydrothermal treatment. A review of the literature was conducted to identify studies by Serbian authors on the topic of biochar for the period between 2018 and 2024. The criteria for inclusion in this review focused on manuscripts authored or co-authored

Table 2. Comparative analysis of charcoal research in Serbia (2004–2024)
Tabela 2. Analiza porównawcza badań nad węglem drzewnym w Serbii (2004–2024)

Application domain	Research focus/purpose	Key findings
Archaeology	Charcoal analysis for environmental reconstruction, ritual use, and settlement practices	Reveals species use, symbolic practices (e.g., funerary), woodland management, and resource selectivity
Fuel, industry	Charcoal production, market structure, and use in metallurgy and household energy	Traditional methods dominate; inefficiencies persist; potential for modernization and export growth
Agriculture	Soil amendment in organic farming using retorted beech charcoal	Increased yield (up to 27%), improved shoot growth, enhanced nutrient/water retention, long-term soil benefits
Adsorption, environmental health	Detoxification, mycotoxin/pesticide removal, wastewater treatment	Effective removal of organophosphates and deoxynivalenol; viable for clinical and food safety applications
Medical applications	Composite systems for wound care and cancer therapy using activated charcoal	Antibacterial, antifungal, and cytotoxic effects via Zn^{2+} and iodine-loaded hydrogels
Radon monitoring	Charcoal canisters for environmental radiation surveillance	High radon levels detected in spas and former mining zones; an effective and low-cost monitoring method

by Serbian scientists that address the production, characterization or application of biochar and related carbon-rich materials. A literature search was conducted using keywords such as "biochar", "char", and "hydrochar", thereby aiming to capture a broad spectrum of research covering thermochemical conversion processes, material properties, and diverse applications in environmental, agricultural, and technological contexts. The literature data are presented according to the source material used for biochar production. The main aspects of this research are summarized in Fig. 1.

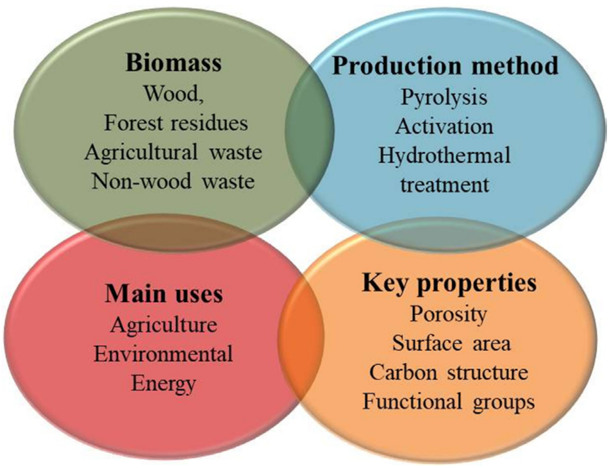

Fig. 1. Main aspects of biochar production and application
Ryc. 1. Główne aspekty produkcji i zastosowania biowęgla

Biochar from wood and wood-processing waste

The most commonly used woods for biochar production are beech, oak, poplar, and pine. Commercial biochar (Basna, Čačak, Serbia), obtained by pyrolysis of a beech–oak wood mixture at 700°C under atmospheric pressure, was used as a feed additive for calves to evaluate its effects on health parameters (Gržin et al., 2019). Blood glucose, total serum protein, and albumin levels were monitored. At a biochar dosage of 0.25% in the feed, a decrease in blood glucose and significant increases in albumin and total serum protein levels were observed in the calves.

The same biochar was also employed as a support for covalent immobilization of horseradish peroxidase (HRP) using glutaraldehyde as a crosslinker (Petronijević et al., 2021). This application improved HRP stability and enabled its reuse over many cycles, while achieving high efficiency in removing phenol from water.

Lubura et al. (2022) investigated the potential of biochar as a reinforcing filler in rubber production, comparing its performance to that of conventional carbon black (CB). The biochar, produced from hardwood waste biomass via hydrothermal carbonization at 215°C and 19.7 bar for 165 minutes, contained trace elements in addition to carbon and oxygen. Compared to CB, biochar showed a lower curing rate during rubber crosslinking. While there was no significant difference in tensile stress at lower elongations (up to 100%), CB-based mixtures exhibited superior reinforcement at higher elongations.

Biochar derived from hardwood has also been shown to effectively remove polycyclic aromatic hydrocarbons (PAHs) from contaminated sediments through in situ remediation, a method less disruptive to ecosystems than ex situ approaches. Beljin et al. (2023) determined that a biochar dose of 0.5% and an aging period of 180 days were optimal for PAH stabilization. Although its stabilization efficacy was lower than that of activated carbon, biochar presented a more cost-effective solution.

Additionally, the use of wood waste for heat generation contributes to sustainability and reduces dependency on fossil fuels. Manić et al. (2023) analysed the performance of wood pellets made from softwood and hardwood sawdust, highlighting that production parameters – such as extrusion length and die temperature – significantly influenced pellet properties. The lignocellulosic composition most strongly affected mechanical strength, while die temperature primarily impacted combustion behaviour. Pellets produced at higher temperatures exhibited reduced effective thermal conductivity and specific heat, which was attributed to a thin solid surface layer composed of waxes and lignin.

Wood-derived biochar demonstrates broad applicability, from improving animal health and supporting enzyme-based water purification to serving as a filler in rubber and aiding in sediment remediation. Its performance depends heavily on the production method and feedstock: high-temperature pyrolyzed biochar shows greater stability and reusability, while hydrothermally produced biochar offers cost-effective but less robust alternatives. Despite some limitations, biochar offers a sustainable, multifunctional solution across environmental, agricultural, and industrial sectors.

Biochar from forest residues

Plane tree seeds were used for the production of activated carbon (Dodevski et al., 2020). The resulting biochar was activated with CO_2 at 750°C and 850°C for 0.3, 1, and 2 hours. The activated biochars were predominantly microporous, with specific surface areas ranging from 426 to 721 m^2g^{-1}. The highest surface area was achieved at 850°C with a 1-hour activation.

Gaseous, liquid, and solid products from the pyrolysis of poplar fluff (*Populus alba*) were characterized to evaluate the fuel potential of this lignocellulosic waste (Janković et al., 2019a; 2021). The estimated higher heating value of poplar fluff (15.86 MJ kg^{-1}) aligns with values typical for lignite or brown coal. Biochar obtained at 850°C exhibited both amorphous and graphitic phases, indicating partial graphitization during carbonization. A potential drawback is the relatively high ash content, which could limit its use in heat boiler systems.

Leaves of *Ailanthus altissima*, an invasive plant species, were used for biochar production and its application in pharmaceutical adsorption (Stojanović et al., 2024a; 2024b). Dried and milled leaves were pyrolyzed at 500°C and 800°C for 2 hours, followed by $ZnCl_2$ impregnation to produce activated carbon. The biochar activated at 800°C exhibited a specific surface area of 346.6 m^2g^{-1} while retaining key functional groups. This material was tested for the adsorption of atenolol, paracetamol, ketorolac, and tetracycline, with removal efficiencies of 34.1%, 51.3%, 55.9%, and 38.2%, respectively. Adsorption mechanisms included hydrophobic interactions, pore filling, and hydrogen bonding. Kinetic studies revealed adsorption capacities of 46.2, 75.3, 88.0, and 113.4 mg g^{-1} for atenolol, tetracycline, paracetamol, and ketorolac, respectively, suggesting greater affinity for less polar compounds.

Cone-like flowers of black alder (*Alnus glutinosa* L.), a lignocellulose-rich biowaste, were identified as a promising precursor for activated carbon (Kandić et al., 2024). The raw material was carbonized and activated at 750°C in a CO_2 atmosphere. The resulting biochar was applied in the inhibition of biofilm formation by eight bacterial strains: *Escherichia coli*, *Pseudomonas aeruginosa*, *Enterobacter cloacae*, *Salmonella Typhimurium*, *Proteus mirabilis*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, and *Enterococcus faecalis*. The most notable biofilm inhibition was observed for E. coli and E. cloacae, with efficiencies of 62.6% and 73.8%, respectively.

This section highlights the diverse use of plant-derived biochar and activated carbon from various biomass sources – plane tree seeds, poplar fluff, *Ailanthus altissima* leaves, and black alder cones – for applications ranging from adsorption to antimicrobial activity. While activation methods and surface areas vary, each material demonstrates functional efficiency tailored to its application: high adsorption for pharmaceuticals, energy potential comparable to low-grade fossil fuels, and notable antibacterial effects, showing how feedstock type and activation conditions critically influence performance.

Biochar from non-wood bio-waste materials

Biochar can also be produced from non-wood biowaste originating from various agricultural and food industry residues. Researchers have investigated the properties of biochars obtained from such materials and applied them for diverse purposes.

The analysis of slow pyrolysis of corn brakes, wheat straw, and hazelnut shells by simultaneous thermal analysis–mass spectrometry revealed that thermal decomposition occurs in three stages: water removal, devolatilization, and biochar formation (Manić et al., 2019). Among the tested samples, hazelnut shell yielded the highest amount of biochar, attributed to its higher lignin content compared to other biowastes.

Sunflower residue carbonized under a constant nitrogen flow at 900°C with a heating rate of 5°C/min and chemically activated by KOH was used for toxic metal removal (Radenković et al., 2024). The resulting biochar exhibited a microporous structure with a specific surface area of 1489 m^2/g and maximum adsorption capacities of 91.8 mg/g for Pb^{2+} and 20.5 mg/g for Cu^{2+}. The main adsorption mechanisms involved inner-sphere complexation with oxygen-containing functional groups and dominant M^+–π interactions.

Fruit stones, abundant agricultural biowaste in Serbia, are attractive raw materials for biochar production. Sour cherry stones (Antanasković et al., 2024a), peach stones (Lopičić et al., 2023; Antanasković et al., 2024b), and apricot kernel shells (Janković et al.,

Table 3. Comparative view of application area and biochar type
Tabela 3. Porównawcze zestawienie obszarów zastosowania i typów biowęgla

Application Area	Biochar Type	Key Benefits/Notes
Agricultural	Wood & forest residues	Soil improvement, plant growth, enzyme immobilization
Environmental remediation	Wood, forest, and food waste biochars	Heavy metal removal, PAH stabilization, dye and pharmaceutical adsorption
Water treatment	Activated carbon from leaves, fruit stones	Removal of pollutants like atenolol, paracetamol, antibiotics
Energy production	Softwood/hardwood pellet biochar	Fuel value similar to lignite, sustainable heat source
Antimicrobial & antibacterial	Black alder biochar	Biofilm inhibition against E. coli and other bacteria
Rubber reinforcement	Wood-derived biochar	Modest reinforcement, lower curing rates compared to carbon black

2019b) have been utilized for biochar synthesis. The resulting biochars have been applied in toxic dye removal, enzyme immobilization, and as precursors for activated carbon or stable fuel materials.

Biochar derived from spent mushroom substrate was shown to be a valuable material for developing adsorbents (Kojić et al., 2022). Additionally, biochar production from the perennial grass *Miscanthus* × *giganteus* (Jevrosimov et al., 2021; Perendija et al., 2024) supports bioenergy generation from biomass used in phytoremediation of contaminated soils.

This section highlights the diverse agricultural and food industry biowastes used for biochar production, with feedstock composition – especially lignin content – strongly influencing biochar yield and properties. Activated biochars from these materials demonstrate effective applications in pollutant removal, enzyme immobilization, and bioenergy, illustrating their versatility and sustainability in environmental and energy contexts.

The application area and biochar type presented in this review are summarized in Table 3.

The application of biochar derived from various biomass sources has been diversified and has shown promising results, offering a sustainable alternative to existing solutions. However, several unresolved issues need to be addressed to fully realize the potential of biochar. Optimization of the production process and clarification of the mechanisms involved in its applications are essential. Additionally, a regulatory framework should be established before scaling up for commercial use can proceed.

CONCLUSION

Charcoal research in Serbia over the past two decades reveals dynamic evolution in both academic focus and practical application. Historically rooted in energy production and metallurgy, charcoal continues to play a significant role in traditional industries and household heating, despite persistent inefficiencies and limited regulatory oversight. Archaeological investigations have demonstrated charcoal's enduring value as a proxy for understanding past environments, cultural practices, and resource management from the Paleolithic to the medieval period. More recently, scientific efforts have expanded charcoal's utility into novel areas such as organic agriculture, adsorption of toxins and pollutants, and even medical applications through the development of activated composite systems. Particularly noteworthy is the use of retorted beech charcoal in improving crop yields and supporting antimicrobial and anticancer treatments.

Recent research on biochar production from diverse biomass sources – including wood, agricultural residues, and invasive plants – shows its wide applicability in environmental remediation, agriculture, and industry. Feedstock composition and pyrolysis or activation conditions significantly influence biochar's properties, which determine its effectiveness in applications such as pollutant adsorption, enzyme immobilization, antimicrobial activity, bioenergy, and material reinforcement. Biomass with higher lignin content tends to yield more biochar with favourable characteristics, while activation methods enhance surface area and adsorption capacity. Despite promising results, challenges remain in standardizing production processes, understanding long-term environmental impacts, and scaling up for commercial use. Future research should focus on optimizing production protocols, clarifying adsorption mechanisms, and conducting extended environmental assessments. From a policy perspective, supporting biochar valorization of biowaste through incentives and regulatory frameworks will be key to promoting sustainable circular bioeconomies and reducing reliance on fossil fuels.

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BADANIA NAD WĘGLEM DRZEWNYM I BIOWĘGLEM W SERBII

ABSTRAKT

W niniejszym artykule przeglądowym zebrano i przedstawiono dane literaturowe dotyczące badań nad węglem drzewnym i biowęglem opublikowane przez serbskich naukowców. Celem opracowania jest prezentacja wyników dotyczących wykorzystania różnych rodzajów materiałów drzewnych, innych niż drewno tartaczne, do produkcji stałych produktów otrzymywanych w procesie pirolizy. Omówiono parametry stosowane w tym procesie, właściwości uzyskanych produktów oraz ich zastosowania.

Słowa kluczowe: węgiel drzewny, biowęgiel, archeologia, adsorpcja, rolnictwo, przemysł