FROM WASTE TO RESOURCE: WOOD WASTE BIOCHAR FOR SUSTAINABLE AGRICULTURE
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NUO ATLIEKŲ IKI IŠTEKLIŲ: BIOANGLIS IŠ MEDIENOS ATLIEKŲ TVARIAM ŽEMĖS ŪKIUI

Jotautienė EGLĖ*[1)], Zinkevičinė RAIMONDA[1)], Teja Sowrya Yannana SIVA[1)]

[1)] Department of Agricultural Engineering and Safety, Faculty of Engineering, Agriculture Academy, Vytautas Magnus University, Studentu Str. 15A, LT-53362 Akademija, Kaunas District, Lithuania;

Tel: +370 68086029; E-mail: egle.jotautiene@vdu.lt

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ABSTRACT

Wood waste is a growing environmental and economic challenge particularly due to disposal costs and loss of recoverable resources in the European Union, with annual volumes reaching 50 million m³ and projected to rise to 59–67 million m³ by 2030. Wood residues, generated from packaging, construction, demolition, and industrial processes, remain underutilized despite their recycling potential. Contamination and inefficient management hinder sustainable reuse, yet literature highlights opportunities for energy recovery, material substitution, and biochar production as part of circular economy. This review synthesizes current knowledge, emphasizing environmental benefits, resource efficiency, and future directions for optimizing wood waste utilization.

SANTRAUKA

Medienos atliekos tampa vis didesne ekonomine ir aplinkosaugine problema Europos Sąjungoje – kasmet susidaro apie 50 mln. m³, o iki 2030 m. prognozuojama, kad jų kiekis sieks 59–67 mln. m. Atliekos susidaro iš pakuočių, statybų, griovimo darbų ir pramonės procesų, tačiau jų perdirbimo potencialas vis dar menkai išnaudojamas. Straipsnyje apžvelgiami medienos atliekų šaltiniai, valdymo iššūkiai ir perdirbimo galimybės, pabrėžiant jų vaidmenį energijos gamyboje, medžiagų pakaitaluose bei bioanglies taikymuose, siekiant žiedinės ekonomikos ir tvarumo tikslų.

INTRODUCTION

Wood waste is currently a major economic and environmental issue. According to scientific studies, around 50 million cubic meters of wood waste are generated in the European Union each year, and by 2030 this volume is projected to rise to 59-67 million cubic meters (*Bergeron.*, *2016; Berger et al., 2020; Mancini et al., 2023*).This is a significant volume that requires urgent, sustainable solutions and actions to mitigate its environmental impact (*Bergeron., 2016; Berger et al., 2020*). Wood, with its unique set of physical and chemical properties, is highly valuable in a wide range of applications such as construction, furniture, packaging, and energy production, and as a natural raw material (*Faraca et al., 2019*). The scientific literature highlights that wood waste is a distinct category of wastes generated from a variety of sources, such as wooden packaging, construction and demolition activities, the wood processing industry, and other sources such as private households and railway construction, where wood products are discarded (*Van Benthem et al., 2007; Pandey., 2022*). It also states that the recycling potential of wood waste is currently not yet fully exploited. This is due to the limited range of sustainable reuse or recycling options (*Ramage et al., 2017; Humar et al., 2006; Berger et al., 2020*). This shortcoming leads to challenges and inefficiencies in this area, despite the existing potential. The potential of wood waste depends on various factors, primarily influenced by the high volume of waste and the presence of potentially harmful substances. European Union statistics on wood wastes are mainly based on the following categories:

- Municipal wood waste;
- Construction and demolition wood waste;
- Industrial wood waste (as a by-product) (*Ihnat et al., 2020*).

This reveals that the potential and recycling potential of these wastes are highly dependent on their source and composition and may have an impact on their subsequent management.

Eurostat is the most important source of comprehensive data on waste management in Europe. These data define the valorisation or disposal of wood waste. However, the analysis of these data has often excluded some undesirable practices such as household heating or open burning. In 2018, the European Commission published the Guidance on Cascading Use of Biomass, which provides model examples for the optimal use of wood biomass. The Circular Economy Action Plan, adopted in 2015, aims to reorient the European economy towards sustainability by promoting sustainable growth and job creation (*Ihnat et al., 2020*). The circular economy which promotes the development of products with a higher proportion of reusable or renewable material, is increasingly attracting the attention of the scientific and policy communities to ensure the most efficient use of resources. Agricultural and forestry activities generate large amounts of plant biomass (residues), which are sometimes simply burned without extracting energy. In addition, burning often takes place in open areas, with negative impacts on both the environment and human health. Such practices result from inadequate biomass management and recycling strategies, so addressing the need for sustainable solutions in these areas is crucial (*Caldas et al., 2020*). The actions of the Circular Economy Roadmap aim to ensure that products and materials are part of a closed-loop system, preserving their economic value, minimizing waste, and increasing recycling and reuse (*Ihnat et al., 2020*). Wood waste recycled into new products can significantly reduce the burden on the environment by using less material, water, and energy in the production process compared to the extraction and use of primary raw materials (*Sathre et al.,* 2006; *Faraca et al.,* 2016). It is particularly important to consider this recycling option in the current critical context of dwindling fossil fuel resources, steadily rising oil prices, and climate change, which increases disaster risks and intensifies efforts to reduce carbon dioxide emissions. Therefore, recycling approaches are becoming a necessary strategy to address these challenges (*Kim et al., 2014*). Such an approach supports both the environmental and economic goals while fostering sustainable development and improving resource efficiency (*Ihnat et al., 2020*).

Wood product manufacturing involves a wide range of processes, from material extraction to the production of final products, often causing pollution of land, air, and water. Approximately half of all harvested wood biomass is used for useful products, with the remainder becoming waste, posing challenges or environmental sustainability (*Zeng et al., 2013; Pandey., 2022*). For every cubic meter of wood harvested and transported, about half is discarded. This includes abandoned logs (3.75%), stumps (10%), tops and branches (33.75%), and wood offcuts (2.5%) (*Garcia et al., 2017; Pandey., 2022*). This means that a significant proportion of wood often remains unused or is discarded as waste without contributing to production processes. These residues can negatively impact the environment and resource efficiency. Therefore, it is crucial to find ways to reduce wood waste and optimize the use of productive resources.

There is a growing demand for wood as a renewable resource, especially in construction and material production industries. Consequently, new consumption patterns are generating an increasing amount of wood waste that can be used as a secondary raw material (*Besserer et al.,* 2021). Currently, wood waste can be used for energy recovery (e.g. in line with the Renewable Energy Directives) or reused as a building material. However, some ecological assessments show contradictory results regarding the effectiveness of these two options, as wood products may contain pollutants that can severely limit the recycling or reuse of wood waste (*Berger et al., 2020; Faraca et al., 2016*). It should be noted that recycled wood waste can substitute for primary raw materials and offer the potential to reduce the costs of harvesting, transport, and disposal, including incineration or landfill (*Kim et al., 2014*).

While wood waste is widely recognized as an environmental and economic challenge particularly due to disposal costs and loss of recoverable resources, it is essential to introduce biochar early in the discussion, as it represents the central focus of this review. Biochar is a highly carbon-rich material produced by pyrolysis, the thermochemical conversion of biomass at high temperatures in the absence of oxygen. It improves soil fertility, enhances water and nutrient retention, and serves as a long-term carbon sink, thereby contributing to climate change mitigation (*Lehmann et al*., *2011*; *Papageorgiou et al*., *2021*). Positioning biochar production from wood waste within the introduction, highlights its role as a promising strategy to reduce waste volumes, support circular economy principles, and generate environmental and agronomic benefits (*Ronsse et al., 2013*).

Accordingly, the aim of this paper is to critically assess the potential of wood waste utilization for biochar production, synthesizing current research on its environmental, technological, and agronomic implications. The central problem addressed is the under-utilization of wood residues, constrained by contamination, management inefficiencies, and limited recycling pathways.

The working hypothesis is that biochar derived from wood waste can serve as an effective solution to these challenges, offering measurable benefits in soil health, carbon sequestration, and resource efficiency. By framing the study around this hypothesis, the paper seeks to provide a synthesis that informs both scientific understanding and policy development in sustainable waste management.

WOOD WASTE TO BIOCHAR

2.1. Overview of the potential for using different types of wood waste

The scientific literature includes numerous life cycle assessments on wood waste management. Many of these emphasize the direct and substitution effects of recycling, landfilling, or incineration of wood waste. However, these analyses often focus solely on the immediate processes without taking into account the broader context and the long-term environmental and economic consequences (*Kim et al., 2014; Bergman et al., 2013; Carpenter et al., 2013; Nuss et al., 2013; Rivela et al., 2006; Morris et al., 2016*). The Life Cycle Assessment (LCA) methodology is a crucial tool for evaluating and analysing the environmental performance of products and services. These factors are essential for the analysis of sustainability and should therefore be incorporated in the decision-making process (*Rivela et al., 2006*).

Recycling and disposal of waste are essential stages of the life cycle of products, which, like every other stage of the cycle, are closely tied to environmental burdens. The waste hierarchy principle (prevention, reuse, recycling, alternative use, disposal) is often referred to in legislation, however, the hierarchy alone does not offer a comprehensive view of the combination of recycling and waste management technologies in integrated waste management systems (*Haupt et al., 2018*).

Most wood waste can be undergoing various treatments, including thermal, chemical, and mechanical treatments. Importantly, this often involves large quantities of preservative-treated wood, which may contain organic and inorganic contaminants (*Berger et al., 2020; Pommer., 2000; Felton et al., 1996*). The literature highlights that wood waste can also be contaminated with other materials. Contaminants are foreign material fractions that can be extracted from wood waste using certain processes such as sorting or mechanical methods like screening, magnetic separation, or eddy current separation. The most common contaminants from other materials are plastics, metals, and concrete. Overall, these material contaminants typically account for 1 to 2% (by weight) of the wood waste stream.

Chemical pollutants originate from substances used to treat wood to extend its lifespan or protect it from physical damage and pests, as well as from the pigments used in the paint. These contaminants are virtually impossible to separate mechanically from wood waste (*Edo et al., 2016*). Wood, despite being a naturally occurring material, often contains various additives and contaminants such as adhesives, varnishes, and paints. Additionally, it may be contaminated with pollutants from woodworking processes, including heavy metals, as well as foreign materials such as glass, plastics, etc. (*Besserer et al., 2021*). These pollutants pose significant challenges for wood waste management as they can pose health risks and environmental problems even after the end of the wood's useful life. Their presence necessitates implementing effective waste management measures to avoid potential negative effects on human health and the environment (*Berger et al., 2020; Shahidul et al., 2018*). For this reason, the efficient recycling or reuse of wood waste could be more effective if the materials were properly sorted and managed according to their quality and properties. The composition of wood waste is an important factor in identifying the optimal recycling options. To provide a high-quality and environmentally friendly recycling process, these wastes must be properly sorted according to the quality class of the material (*Mancini et al., 2023*).

Different sources refer to various methods of classifying wood waste: based on the level of treatment and on the method of generation. Wood waste could be categorized into these groups based on origin and treatment: clean (virgin) wood waste, non-hazardous treated wood waste, and hazardous treated wood waste. Clean wood waste, which complies with international standards, can already be utilized in incineration plants, where Hazardous treated wood waste containing pollutants such as copper, chromium, or arsenic is classified as hazardous (*Nzihou et al., 2013; Cesprini et al., 2020*). The handling of clean wood waste is a complex issue that varies from country to country, even ISO standards are recognized (*Cesprini et al., 2020; Tatàno et al., 2009*).

Besserer and other researchers suggest dividing wood waste into two main categories: Industrial waste, which is generated in industry, and End-of-life waste, which is generated after the use of products (*Besserer et al., 2021*). The literature highlights that wood waste has multiple applications, including wood production, energy production (heat and electricity), mulching and animal feed. Such raw materials, although inexpensive and often underutilized, can significantly increases the economic value of wood waste (*Pandey, 2022*).

The classification of wood waste is often based on its generating type. Wood waste from forest harvesting is generated from harvesting timber in forests. These residues that extend beyond the felled trees include surrounding trees damaged during logging. Collecting and transporting these materials to processing sites is a major challenge due to the difficult terrain and poor road conditions, rendering much of this waste unusable (*Haryanto et al., 2021*). The second category is waste from the wood processing industry. Examples of wood waste forms mentioned in the scientific literature include sawn timber, veneer, wood chippings, etc. The woodworking industry includes wood processing, furniture manufacturing, and wood products. The woodworking processes in a sawmill typically include dismantling, resawing, and edge trimming (*Haryanto et al., 2021; Balsiger et al., 2000*).

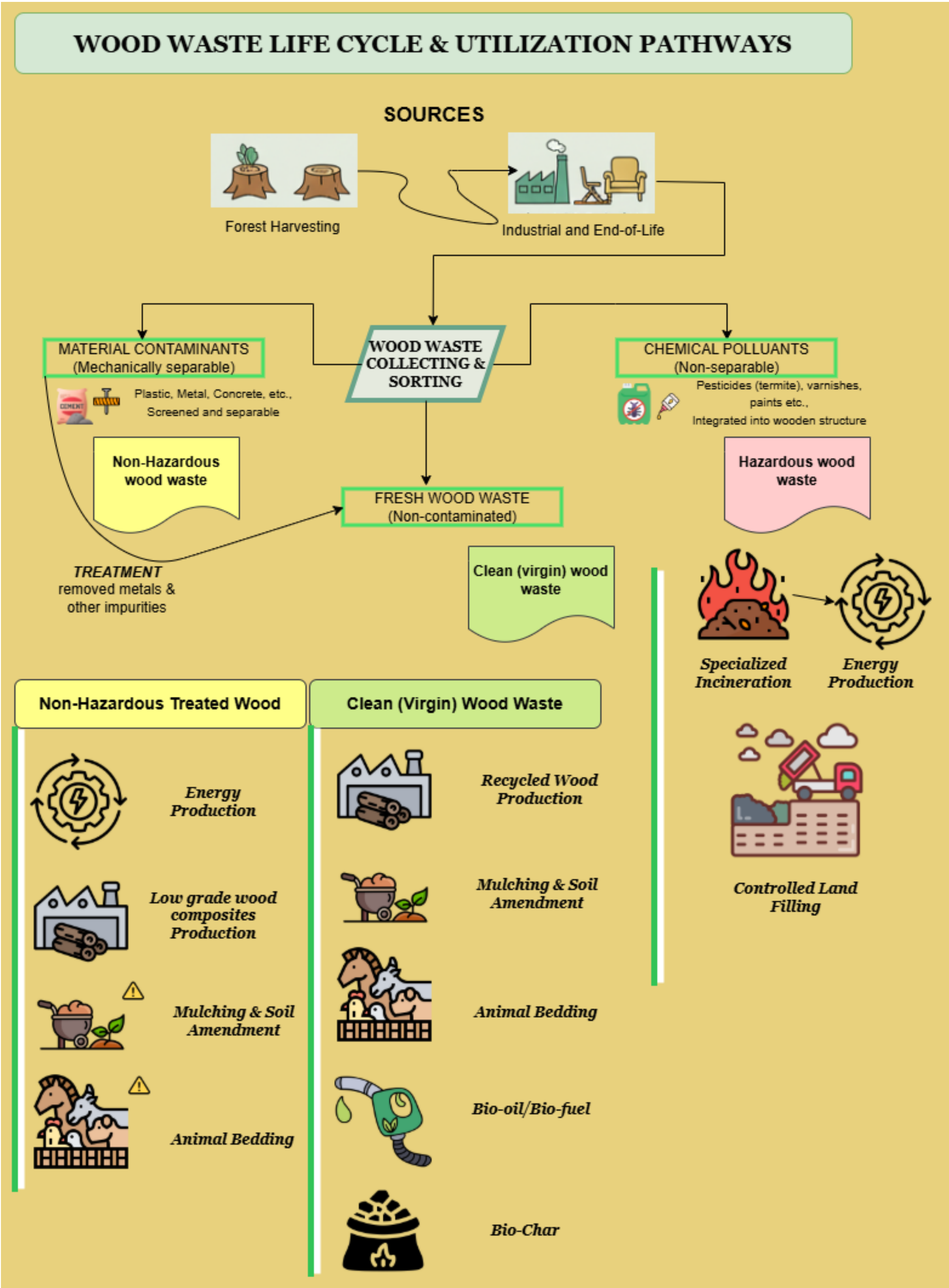

Fig. 1 - The classification and potential uses of wood waste

The utilization of wood waste for various purposes can be summarized into the following categories in Figure 1. Wood waste has significant potential recovery options, contributing to the sustainable use of resources.

Minimizing wood waste enhances the efficiency of primary wood utilization and ensures the sustainable use of forest resources, avoiding additional impacts on the world's forests (*Pandey, 2022; Magin et al., 2001*). Wood waste is a valuable alternative energy source and a raw material for producing a variety of products, including chemicals, bio-oils, and other lignocellulose-based products (*Pandey, 2022; Packalen et al., 2017*). Wood bark, which contains fatty and water-soluble extracts, can be transformed into valuable products such as chemicals for the cosmetics and pharmaceutical industries (*Pandey, 2022; Routa et al., 2017*).

In addition, wood waste serves as a source of bio-oil, which is effectively used as a modifier for petroleum asphalt binders and a plasticizer to enhance asphalt properties (*Pandey, 2022; Yang et al., 2014*). Other value-added applications of wood waste include the production of biofuels and wood composites (*Pandey, 2022; Eshun et al., 2012*). These technologies provide opportunities to optimize the use of wood waste and contribute to the circular economy.

Biochar is one of the promising areas of wood waste recycling, which is particularly relevant for agriculture due to its environmental and economic advantages. The use of wood waste for biochar production not only reduces waste but also contributes to carbon capture and long-term storage in the soil, a vital step in mitigating climate change. Biochar, a carbon-rich material derived from biomass such as wood residues, possesses unique physicochemical properties that make it highly valuable for sustainable applications (*Liu et al., 2021; Joseph et al., 2021*). As biochar is a highly carbon-rich material, it is valuable not only as a soil improver, but also for increasing yields and reducing the use of chemical fertilizers. Given the wide range of properties and compositional diversity of wood waste, biochar production technologies can be adapted to maximize the value of the waste. In this context, biochar production becomes a natural extension of the integrated strategy for utilizing wood waste, which encompasses existing pathways such as energy production, engineered wood products, and chemicals, while ensuring the sustainable implementation of the circular economy principles.

Although numerous studies emphasize the benefits of biochar derived from wood waste, the literature reveals inconsistencies that require critical attention. For example, while several authors report significant improvements in soil fertility and water retention, others highlight limited or context-dependent effects, particularly in clay soils or contaminated environments (*Liu et al., 2021; Kavitha et al., 2018*). Similarly, results on heavy metal immobilization vary, with some studies showing reductions above 90% (*Houben et al., 2013*), whereas others note lower efficiency depending on biochar type and application rate. These discrepancies suggest that standardized methodologies and long-term field trials are still lacking. Therefore, future research should focus on harmonizing experimental approaches and exploring innovative modifications of biochar to enhance its agronomic and environmental benefits.

2.2. Feasibility of biochar production from different types of wood waste

The scientific results showed that biochar has a huge impact on protecting the environment and developing sustainable agriculture (*Lu et al., 2020; Muhammad et al., 2021*). The literature indicates that various forms of biochar from different raw materials, such as wood waste, crop straw, animal manure, sewage sludge, and food residues, are processed by pyrolysis at temperatures ranging from around 350℃ to over 750℃. This technology allows for the creation of a carbon-rich material used in a wide range of industrial sectors, including energy production and the chemical industry (*Joseph et al., 2021*). The wooden raw material consists mainly of cellulose, hemicellulose, lignin, and small amounts of inorganic materials. For example, birch wood contains 40% cellulose, 26% hemicellulose, and 16% lignin (*Mohan et al., 2021; Rathnayake et al., 2023*). During pyrolysis, these compounds are gradually degraded as the temperature increases. Hemicellulose and cellulose start to degrade first at 220℃–315℃ and 315℃–400℃, respectively (*Rathnayake et al., 2023; Yang et al., 2007*). Lignin degradation occurs over a wide temperature range (100℃–900℃) (*Rathnayake et al., 2023; Zhao et al., 2017*).

Biochar is attracting growing interest because of its distinctive characteristics, including its carbon-rich composition, extensive surface area, cation exchange capacity, and durable structure. The physicochemical characteristics of biochar are different for each raw material used (*Wang et al., 2019*). Pyrolysis is a thermal decomposition method that occurs under anoxic conditions (*Castro et al., 2010; Uddin et al., 2018*). Pyrolysis can be used to treat biomass and is typically categorized by its heating rate and residence time as flash, fast, and slow pyrolysis (*Fahmy et al., 2020*). It is also reported that slow pyrolysis produces higher yields of biochar (36%) than fast pyrolysis (about 17%) or gasification (12%) (*Oni et al., 2019*).

The biochar produced to date by adapting the pyrolysis process is mainly used as an energy source for metal casting, smithery, filters, and flavouring in food production. This is attributed to the high energy of biochar, approximately 29 MJ/kg, which is significantly higher than that of biomass or bio-oil (*Haryanto et al., 2021*). However, biochar has a wider potential and higher added value, for example, as a soil improvement material, in the production of activated carbon, electrode material, or graphene. It should be noted that biochar generated through slow pyrolysis typically has a smaller surface area compared to biochar produced via fast pyrolysis or gasification (*Haryanto et al., 2021*).

Biochar is characterized by its alkaline pH, high surface area, exceptionally high porosity, durability, and an abundant number of oxygen-containing surface functional groups. Biochar is a multifunctional material with diverse characteristics that influence a variety of applications ranging from the removal of pollutants to industrial processes (*Liu et al., 2021; Lebrun et al., 2021; Liu et al., 2017*). Biochar, when mixed with soil enriches the available nutrients and prevents leaching, and to stimulate the activity of important agricultural microorganisms. It acts as an effective carbon sink by absorbing atmospheric CO_2 and storing it in the soil, thereby reducing the release of other greenhouse gases. It also helps reduce the negative effects of agrochemicals (e.g. by reducing nutrient Leaching). Its ability to retain moisture can reduce water loss and improve the water availability for plants, which is especially important during the dry season or when water is scarce. This means that biochar from wood waste can be a valuable tool in plant production and soil maintenance, contributing to more fertile and healthier plant growth (*Liu et al., 2021; Hossain et al., 2010; Spokas et al., 2012*).

Biochar derived from wood waste is commonly described in scientific studies as a stable soil amendment that enhances and replenishes organic matter, improves water retention, and optimizes soil structure. It also supplies essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S), which are vital for supporting plant growth and development (*Liu et al*., 2021; *Gajalakshmi et al*., 2008; *Kumpiene et al*., 2008; *Lannan et al*., 2013). These properties determine the efficacy of biochar in solving crop and livestock production problems (*Kalus et al*., 2019; *Banik et al*., 2019). The application of biochar from wood waste in agriculture induces significant changes in the soil's physical, chemical and biological characteristics, alongside modification to the carbon balance. These changes can also impact the carbon cycle and its overall balance (*Das et al., 2023*). Biochar has applications, among others, as an additive in composting or mixing with soil. Its use can improve the fertilizer use efficiency, which influence soil quality. It can also sorb pollutants from soil and water, which play an important role in the environmental protection. Biochar added to the soil, along with organic carbon and various macro- and micronutrients, becomes a valuable source of raw materials for plant growth and soil microflora (*Malińska, 2012; Malińska et al., 2015; Czekała et al., 2019*).

The scientific literature highlights the impact of biochar and other organic additives in improving soil quality and increasing plant productivity in depleted or contaminated soils (*Liu et al., 2021; Kammann et al., 2016; Głąb et al., 2018*). The main effect of biochar on organic matter degradation is related to its ability to support microbial growth in the composting matrix. Increased microbial activity at biochar composting sites accelerates the degradation of organic matter, leading to the breakdown of complex biopolymers into simpler organic compounds (such as amino acids, small carbohydrates, and phenolic compounds) (*Sanchez-Monedero et al., 2018*). Biochar produced from wood waste used in conjunction with manure retains nutrients and can stabilize inorganic pollutants through adsorption, binding and contributing to their precipitation (*Liu et al., 2021; Kumpiene et al., 2008; Karami et al., 2011; Cui et al., 2020; Wang et al., 2020*). Biochar can effectively retain NH_3, NH_4+, and NO_3^- in animal manure (*Adekiya et al., 2019; Steiner et al., 2010*).

As shown in the Figure 2, the physicochemical properties of biochar, such as particle size of the biochar and its depth of incorporation, influence the overall water retention capacity. In sandy soils, biochar has the highest water retention capacity with particle sizes ranging from 0.5 to 1.0 mm. The optimal depth of biochar incorporation is between 4 and 6 cm. Additionally, the concentration of biochar is important, as it also affects the soil's water retention capacity (*Ibrahim et al., 2017; Kavitha et al., 2018*). The water retention capacity of clay soils can increase by up to 60% at biochar concentrations above 3%. Optimal biochar concentration, however, should be determined individually based on the specific conditions. In sandy loam soils, higher biochar concentrations (> 5%) can reduce pore size, which negatively impacts hydraulic conductivity (*Kavitha et al., 2018; Kameyama et al., 2016; Devereux et al., 2012*).

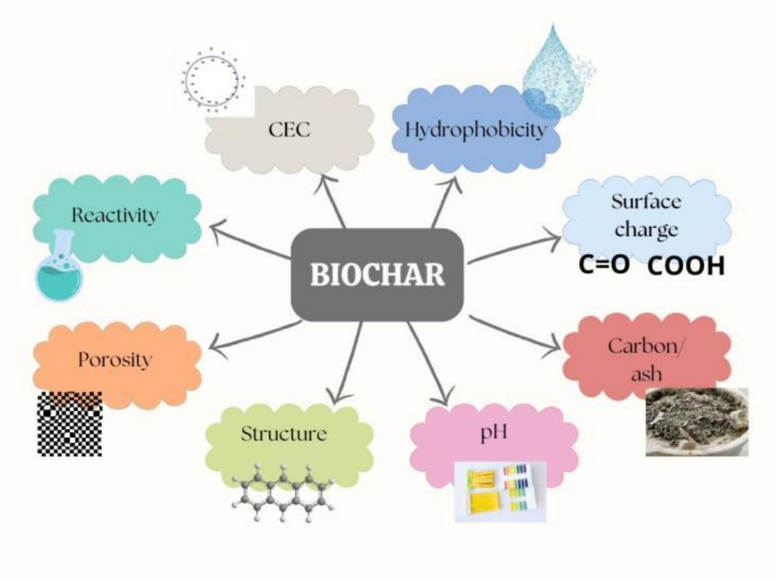

Fig. 2 - Physical and chemical properties of biochar

There is a growing global concern about heavy metal contamination in soils, which has led to an increased emphasis on the need to restore these contaminated soils. The use of biochar in soil remediation is becoming more and more popular as it is acknowledged as an efficient way to immobilize heavy metals in contaminated soils (*He et al*., 2019).. Biochar has been successfully applied to reduce the uptake of toxic heavy metals from soil, including Pb, Cd, and As. This is attributed to the adsorption of metals onto the negatively charged surface areas of biochar particles (*Kavitha et al., 2018; Buss et al., 2012*). Firstly, smaller-sized biochar particles trap metals in the soil. The reason is that the increased surface of biochar particles enhances the metal absorption, thereby reducing the number of metals entering into plant tissues (*Kavitha et al., 2018; Zhang et al., 2013*). *Houben et al. (2013)* determined that the usage of biochar reduced the amount of bio-available (CaCl2 extracted) Cd, Zn, and Pb by 71%, 87% and 92%, respectively. Biomass production increased threefold following biochar application (*Houben et al., 2013; Wang et al., 2020*).

The properties of different biochar produced from wood waste affect plant uptake, so these properties play a very important role (Kavitha et al., 2018; Yang et al., 2017). Biochar can absorb or bind heavy metals through complexation, reduction, cation exchange, electrostatic attraction, and catalytic phenomena. This can transform the solid metals from their inorganic form into an organic form, altering their mobility and biophysical accessibility, which can enhance the soil's agronomic performance. These interactions make biochar's mechanisms for heavy metal stabilization essential in soil remediation processes (Cheng et al., 2020). Beyond factors such as pyrolysis temperature and substrate, other studies show that biochar modifications can affect metal uptake. For example, using biochar modified with manganese admixtures, a decrease in arsenic content in rice plants in contaminated soil and a 9% increase in amino acid content were observed (Kavitha et al., 2018; Yu et al., 2017). In addition, research has shown that combining biochar with other substances, such as limestone, can significantly decrease the absorption of cadmium by wheat and rice plants, with reductions of over 80% observed in both straw and grain. Similarly, research has shown that using sewage sludge biochar at application rates of 1-4% in combination with stabilizing agents like fulvic acid and phosphogypsum can successfully reduce the uptake of heavy metals in maize plants (*Kavitha et al., 2018; Huang et al., 2017*).

The use of biochar to stabilize soil contaminants is increasingly being adopted as a method for remediating polluted soils (*IPCC, 2019*). Currently, biochar is used for a CO_2 sequestration method (*Papageorgiou et al., 2021; IPCC, 2019*). The production of biochar and its incorporation into the soil is an excellent solution for atmospheric CO_2 sequestration (*Papageorgiou et al., 2021; Lehman et al., 2009*). Biochar offers numerous benefits for improving soil quality and achieving environmental sustainability goals. For instance, it's highly porous structure enhances the retention of water and nutrients in the soil, reducing runoff and making essential resources more accessible to plants (*Mohammadi et al., 2021*). Furthermore, biochar serves as a long-term carbon storage medium, playing a significant role in reducing atmospheric carbon dioxide levels (*Chen et al., 2024*). Its use also decreases the volume of organic waste, thereby alleviating the burden on landfills and lowering greenhouse gas emissions produced by waste decomposition (*Chen et al., 2023*).

Additionally, research has demonstrated biochar's capacity to mitigate soil contamination by heavy metals and other pollutants, thereby improving environmental quality (*Lehmann et al., 2011*). Moreover, integrating biochar production and application into agricultural practices supports circular economy models, promoting sustainable resource management and reducing reliance on synthetic fertilizers (*Ronsse et al., 2013*).

Emerging technologies offer promising directions for improving biochar production and application. Hybrid pyrolysis systems, advanced granulation techniques, and chemical or biological modifications of biochar are being explored to enhance its stability and agronomic performance. Integrating biochar with precision agriculture tools and renewable energy systems could further increase efficiency and scalability, ensuring that wood waste is valorised in innovative and sustainable ways.

2.3. Study on the application of biochar from wood waste to the production of fertilizers

This study was designed to provide a broad overview of the current research on biochar derived from wood waste in agriculture, focusing on summarizing key findings. Acknowledging the importance of detailed comparison, the primary aim was to compile relevant research in a structured manner, offering a comprehensive understanding of existing knowledge and emerging trends. Recently, integrative approaches combining biochar with fertilizer have become popular. These approaches aim to increase crop yields and use irrigation water more efficiently, mitigate issues related to insufficient water supply (e.g. drought) and weak fertility of the soil (*Muhammad et al., 2021; Faloye et al., 2019*). A study conducted by *Adekiya et al. (2019)* revealed that the application of biochar, either in conjunction with poultry manure or as a standalone treatment, had a profoundly positive impact on the soil's physical characteristics, including decreased bulk density and increased porosity and moisture retention. Furthermore, the treatment also enhanced the soil's chemical composition, leading to adjustments in pH levels and elevated concentrations of essential nutrients such as organic matter, nitrogen, phosphorus, potassium, and other nutrients. The application of biochar without poultry manure also improved soil chemistry, which revealed a significant interactive effect of biochar and highlighted its beneficial effect on the nutrient use efficiency of poultry manure (*Adekiya et al., 2019*).

Biochar, when combined with compound fertilizers, represents a new technology that can be developed to address specific need of soil and plants. This technology combines biochar with mixed nutrients, minerals, etc. It should be noted that there is limited knowledge regarding the behaviour of biochar with compound fertilizers over successive and non-repeated applications on various plants (*Farrar et al., 2022*).

Liu et.al. (2021), investigated the effects of biochar, chicken manure, and their combined application on maize growth, soil properties, and Pb stress. The study revealed that both biochar and chicken manure, whether applied individually or both, enhanced maize growth, antioxidant enzyme activity, and soil enzyme activity under Pb stress. These amendments also lowered Pb concentrations in maize tissues and reduced the availability of Pb in the soil. Pure biochar proved to be more effective at increasing soil pH, minimizing Pb transfer from soil to plants, and immobilizing Pb. Conversely, pure chicken manure had a stronger influence on promoting maize growth and enhancing antioxidant enzyme activity in the leaves. When applied separately, a higher rate of biochar or manure was more effective in improving maize growth, increasing antioxidant enzymatic activity, and reducing Pb levels in both plants and soil. The combination of biochar and chicken manure exhibited a synergistic effect, further enhancing plant growth, boosting antioxidant enzyme activities, and reducing Pb stress effects by immobilizing Pb. Overall, the combined use of biochar and chicken manure had additive effects on plant growth and soil health. These findings highlight the potential of biochar and chicken manure as complementary amendments for remediating Pb-contaminated soils and supporting plant growth (*Liu et al., 2021*). In another study it was found that high rates of organo-mineral biochar fertilizer increased soil P and K levels at 30th week (harvest) after planting compared to all other treatments. While low rates of organo-mineral biochar fertilizer were like an organic control in terms of P and K. The biomass performance of commercial biochar fertilizer was significantly lower compared to other treatments because the rates used had lower nutrient concentrations (*Farrar et al., 2019*). This study suggests the potential for integrating biochar produced from wood waste with manure, an agricultural by-product, to create granular fertilizers. This approach is recommended due to the challenges associated with producing pure biochar pellets (*Gaudutis et al., 2023*). Integrating wood waste utilization into this circular economy would be in line with current European and global efforts to reduce climate change, reduce greenhouse gas emissions and promote the use of renewable resources.

The prospects for biochar produced from wood waste are particularly promising, with a focus on optimising production methods, increasing the use of biochar in sustainable agriculture, and addressing the challenges of fertiliser pelletization. As was mentioned above, around half of all wood produced is currently used to produce valuable products, while the remaining half often becomes waste, posing major environmental sustainability challenges. For every cubic metre of wood harvested and transported, almost half is discarded, especially stumps which are often underutilized in current material processes. As a result, it simply rots in piles, contributing to negative impacts on the environment and resource efficiency. The use of biochar derived from this stump waste is a viable and innovative solution to reduce waste, improve resource utilisation and support the development of sustainable agricultural practices in the future.

In summary, it can be stated that although many issues related to biochar production from wood waste have been resolved, the following guidelines can be highlighted: Research into advanced biochar production technologies and manufacturing of hybrid fertilizers; Integrating hybrid fertilizers into precision agriculture; Search alternative raw materials for biochar production, and other related avenues of production

Despite the progress made in biochar research, several critical questions remain unresolved. Long-term field studies are scarce, making it difficult to assess the durability of biochar's benefits under diverse climatic and soil conditions. Moreover, uncertainties persist regarding its interactions with soil microbiota, its influence on greenhouse gas emissions, and its economic feasibility across different agricultural systems. Addressing these gaps is essential to establish a more comprehensive understanding of biochar's role in sustainable resource management.

Despite the progress in research on wood-waste-derived biochar, there is still a lack of integration between scientific findings and policy or technological innovation. Current European strategies, such as the Circular Economy Action Plan, emphasize recycling and resource efficiency, yet they rarely provide specific frameworks for biochar deployment in agriculture or waste management (*Ihnat et al*., 2020). Moreover, technological barriers remain, particularly in scaling up granulation processes and ensuring consistent biochar quality across different feedstocks (*Muhammad et al*., *2021*; *Adekiya et al*., *2019*). Addressing these gaps requires coordinated policies that incentivize biochar adoption and targeted research into advanced processing technologies, which will ensure that wood waste can be fully valorised within sustainable systems.

This review highlights both the established knowledge and the areas requiring deeper investigation. The environmental and agronomic benefits of wood-waste-derived biochar are well documented, while also exposing inconsistencies across studies and technological limitations call for more critical, comparative, and interdisciplinary approaches. Future research should focus on harmonizing experimental methodologies, testing biochar under real-world conditions, and integrating scientific findings with policy frameworks. Such efforts will ensure biochar research transfers into effective implementation for advancing circular economy strategies. Future research directions:

- Conduct long-term field trials to evaluate the durability of biochar effects under diverse soil and climate conditions.
- Standardize methodologies for biochar characterization and application rates to improve comparability across studies.
- Investigate biochar–soil microbiota interactions and their implications for nutrient cycling and greenhouse gas emissions.
- Explore innovative technologies such as hybrid pyrolysis, advanced granulation, and chemical/biological modifications of biochar.
- Assess the economic feasibility and scalability of biochar production from wood waste in different sectors.
- Integrate biochar research with policy frameworks to support its adoption in agriculture and waste management.

CONCLUSIONS

Wood-waste-derived biochar offers significant potential for advancing sustainable resource management and climate mitigation. Current evidence demonstrates benefits for soil fertility, nutrient retention, and pollutant stabilization, yet outcomes remain variable across contexts. These inconsistencies highlight the need for standardized methodologies, long-term trials, and innovation in production technologies. By consolidating existing knowledge and identifying research gaps, this review underscores biochar's role as a circular economy strategy and a tool for environmental resilience.

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