Chapter 2

BIOCHAR FOR SUSTAINABLE ENERGY STORAGE APPLICATIONS AND TURKIYE'S BIOCHAR POTENTIAL FROM WASTE

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1. Introduction

The rapidly increasing global population, advancing technologies, and industrialization are causing a continuous rise in energy demand worldwide. Currently, a large portion of energy is derived from fossil fuels, whose reserves are rapidly depleting and which lead to serious environmental problems such as global warming and climate change. In this context, the development of low-carbon, clean, and renewable energy systems has become a vital necessity both for ensuring energy supply security and for reducing environmental degradation. For the sustainability of energy systems, focusing solely on renewable energy production is not sufficient; the efficient and long-term storage of the produced energy also holds critical importance (Shkatulov, Houben, Fischer, & Huinink, 2020; Shrivastava, Gill, Juyal, Lal, & Jain, 2025). The increase in global energy demand, climate change, and environmental pollution concerns are increasing the need for sustainable energy sources and efficient energy storage systems day by day (Kalla, Mayilswamy, Kandasubramanian, & Mahajan-Tatpate, 2024; Liu, Jiang, & Yu, 2019). Reducing dependence on fossil fuels and decreasing carbon emissions are among the priority objectives of the energy sector. In this pursuit, biochar, a carbon-rich material obtained from lignocellulosic biomass, emerges as a prominent candidate due to its potential applications in various sectors (adsorption, catalysis, and gas storage), including energy storage (Konwar, Boro, & Deka, 2014).

From a mechanical engineering perspective, the use of biochar in energy storage devices requires interdisciplinary approaches such as materials science, thermodynamics, electrochemistry, and system integration (Das, Pektezel, & Sımsek, 2025). This book chapter will examine in detail the production techniques of biochar, its physicochemical properties, its role in sustainable energy storage applications, and particularly the biochar production potential from Turkey's abundant biomass wastes. Furthermore, the challenges faced by biochar-based energy storage systems and future perspectives will also be addressed. This study aims to shed light on new research and development areas for a sustainable energy future by highlighting the potential of biochar in energy storage technologies.

2. Biochar: Structure, Properties, and Production Methods

Biochar is a carbon-rich, solid material obtained through the thermal decomposition (pyrolysis) of biomass in an oxygen-free or limited-oxygen environment (Ahmed et al., 2024; Simon, Harikumar, & Sreeja, 2025). This process enables the conversion of a wide range of organic materials, from wood to food waste, into a valuable resource for energy storage and various environmental applications. The unique physical and chemical properties of biochar make it a promising candidate for sustainable technologies.

2.1. Biochar Feedstocks

The final properties of biochar are largely dependent on the type and composition of the feedstock used. Feedstocks can generally be classified as follows:

- **Woody Biomass:** Lignocellulosic materials such as forest residues, tree bark, sawdust, and pruning waste are widely used for high-quality biochar production due to their high carbon content and low ash ratio (Ahmed et al., 2024).
- **Agricultural Biomass:** Post-harvest residues such as corn stover, wheat straw, rice husks, hazelnut shells, and olive pits represent abundant and renewable feedstock sources. This category of biomass typically exhibits elevated ash and potassium content (Ahmed et al., 2024; Simon et al., 2025).
- **Urban Biomass:** The organic fraction of municipal solid waste, encompassing food waste, park and garden trimmings, and sewage sludge, offers a dual benefit by addressing waste management challenges while serving as a valuable biochar precursor (Ahmed et al., 2024).
- **Industrial Biomass:** Organic waste streams originating from food processing, paper manufacturing, and furniture industries are viable for biochar production. The inherent homogeneity of these waste materials can facilitate the standardization of the production process (Ahmed et al., 2024).
- **Specialized Biomass Sources:** Other organic materials, including animal manure and algae, also present significant potential for biochar generation. Algae, in particular, are noteworthy due to their rapid growth rates and minimal requirement for agricultural land (Simon et al., 2025).

2.2. Fundamental Charecteristics of Biochar

Biochar is characterized by a suite of distinctive properties, including a high carbon content, expansive surface area, substantial cation exchange capacity (CEC), and a robust structural integrity. These attributes are predominantly governed by the nature of the feedstock material and the specific processing parameters employed during its production. Consequently, the efficacy of biochar in energy storage applications is intrinsically linked to its optimized physical and chemical characteristics.

Physical Properties:

- **Surface Area and Porosity:** Biochar typically exhibits a hierarchical porous structure, comprising micropores, mesopores, and macropores. A high specific surface area (as determined by BET analysis) significantly enhances the interfacial contact between the electrode and electrolyte, thereby facilitating the efficient transfer of ions and electrons. This characteristic directly influences both the capacitance and the charge/discharge rates of energy storage devices (Kalla et al., 2024; Simon et al., 2025).
- **Density and Structure:** Its inherently low density coupled with a robust structural framework enables the development of lightweight energy storage devices. The carbonaceous matrix of biochar is commonly a composite of amorphous and graphitic domains, with the latter being crucial for augmenting electrical conductivity (Ahmed et al., 2024).
- **Electrical Conductivity:** The electrical conductivity of biochar is directly correlated with its degree of graphitization. Elevating the pyrolysis temperature to approximately 1000 °C is instrumental in producing highly graphitized biochar, which possesses superior electrical conductivity.

Table 1. Role of Biochar's Key Properties in Energy Storage

Property	**Definition**	**Significance for Energy Storage**
High Surface Area	Total surface area per unit mass.	Expands the electrode-electrolyte interface, thereby increasing ion storage capacity.
Porous Structure	Presence of pores of varying sizes.	Facilitates rapid diffusion of electrolyte ions, enhancing power density.
Electrical Conductivity	Ability of the material to conduct electric current.	Enables swift electron transfer and reduces internal resistance.
Surface Chemistry	Type and density of functional groups on the surface.	Improves wettability and provides additional storage through pseudocapacitance.

Chemical Properties:

- **Carbon Content and pH:** A high carbon content (typically 70-90%) forms the fundamental conductive backbone of the material. Biochar generally exhibits an alkaline pH, which can be advantageous for certain electrochemical reactions (Ahmed et al., 2024).
- **Chemical Composition and the Effect of Pyrolysis Temperature:** The elemental composition of biochar is not limited to C, H, and O; it can also incorporate heteroatoms such as S, N, and P, depending on the feedstock. Elevated pyrolysis temperatures lead to a reduction in oxygen (O) content and lower O/C and H/C molar ratios due to the decrease in carboxyl groups. This process enhances carbonization, thereby increasing the environmental stability of biochar. Biochar produced at higher temperatures typically possesses a more refractory (decomposition-resistant) structure.
- **Surface Functional Groups:** Oxygen-containing functional groups, such as carboxyl (-COOH), hydroxyl (-OH), and phenolic groups, present on the biochar surface, enhance the material's wettability and contribute additional energy storage capacity through pseudocapacitance mechanisms (Liu et al., 2019).
- **Inorganic Components (Ash):** Inorganic minerals (ash) originating from the feedstock and formed during production can influence biochar's conductivity and catalytic activity. In some instances, these minerals may function as active sites in lithium/sodium-ion batteries (Simon et al., 2025).

2.3. Production Technologies

Biochar is synthesized through the thermal decomposition (thermochemical conversion) of biomass in an oxygen-free or partially oxygenated environment. A diverse array of thermochemical conversion technologies exists for biochar production. The primary thermochemical methods include pyrolysis, gasification, and hydrothermal carbonization. Each technology influences the yield and characteristics of products such as biochar, bio-oil, and syngas under distinct operating conditions.

2.3.1. Pyrolysis

Pyrolysis stands as the most prevalent method for biochar production, involving the thermal degradation of biomass in an oxygen-deficient (inert gas) atmosphere within a temperature range of 350-1000°C. Product yields are modulated by parameters such as temperature, heating rate, and residence time. Three principal types of pyrolysis are recognized:

- **Slow Pyrolysis:** Characterized by low heating rates and extended reaction durations, slow pyrolysis primarily aims to maximize solid biochar yield (35-50%). Temperatures typically range from 300–900°C, employing very low heating rates (5-10 °C/min) and prolonged residence times (exceeding 1 hour or even days).
- **Fast Pyrolysis:** Designed to maximize liquid bio-oil production (up to 75%) through high heating rates and short reaction times. This process necessitates very high heating rates (>200 °C/min) and extremely brief reaction durations. While fast pyrolysis reduces biochar yield, the resulting biochar byproduct possesses high carbon content and stability.
- **Flash Pyrolysis:** Utilizes exceptionally high heating rates and ultra-short reaction times to optimize the yields of bio-oil and gaseous products (Kalla et al., 2024).

2.3.2. Gasification

Gasification involves the conversion of biomass into syngas at high temperatures, typically above 700°C, in the presence of a controlled amount of a gasifying agent such as oxygen, air, or steam. The primary output is syngas, which is rich in hydrogen and carbon monoxide. Biochar (char) is generated as a significant byproduct, albeit with lower yields, during this process. Biochar derived from gasification, produced at elevated temperatures (e.g., above 750 °C), exhibits a denser structure. Gasification with feedstock mixtures containing high ash content can lead to pore blockage, consequently reducing the surface area.

2.3.3. Hydrothermal Carbonization (HTC)

HTC is a thermochemical conversion process of biomass conducted in the presence of water, under moderate-to-high pressure, and at relatively low temperatures (180–250°C). This method is particularly well-suited for biomass with high moisture content (e.g., aquatic plants, algae, sewage sludge), as it obviates the need for pre-drying. The solid product obtained from HTC is termed hydrochar. Hydrochar generally possesses a greater abundance of surface functional groups (hydroxyl and carbonyl) and higher microporosity compared to pyrolysis biochar.

2.3.4. Torrefaction

Torrefaction is a mild pyrolysis pre-treatment performed at lower temperatures, typically within the 200-300°C range. This process effectively removes moisture from the biomass, enhances its energy density, and renders it more brittle and hydrophobic. The objective is to reduce the oxygen and hydrogen content of the biomass, thereby increasing its carbon ratio and energy content. Torrefaction leads to the complete degradation of hemicellulose. The primary product is torrefied biomass, which is predominantly utilized as fuel rather than for energy storage applications (Ahmed et al., 2024).

2.3.5. Advanced Production Methods

- **Microwave-Assisted Carbonization:** This critical technology facilitates the conversion of biomass by enabling faster and more homogeneous heating through microwave energy, as opposed to conventional external heating. Microwave heating promotes internal-to-external heating, offering advantages such as high heating rates, uniform heating, and superior energy conversion efficiency. This method holds the potential to produce biochar with a higher surface area while consuming less energy (Shrivastava et al., 2025). The implementation of automated control systems and intelligent obstacle avoidance algorithms in robotic material handling systems (Yıldırım & Yaşar, 2015) can further optimize the microwave-assisted carbonization process by ensuring consistent feedstock positioning and minimizing operational interruptions.
- **Laser and Plasma-Assisted Carbonization:** High-energy laser-assisted methods can induce the formation of unique carbon structures (e.g., graphene-like layers) by providing extremely rapid heating rates, though they incur high energy costs (Peng et al., 2024). Plasma-assisted pyrolysis involves the conversion of biomass within a reactive plasma region, rich in electrons and ions generated by high-energy radiation. Plasma energy rapidly heats the feedstock, transforming it into hydrogen and light hydrocarbons. This technique can also serve as an activation/modification method to enhance biochar's surface properties and improve its performance in energy storage applications.
- **Catalytic Pyrolysis:** The incorporation of catalysts into the pyrolysis process can alter reaction pathways, allowing for the tailored development of biochar's pore structure, surface area, and functional groups to meet specific requirements (Ramos, Abdelkader-Fernández, Matos, Peixoto, & Fernandes, 2022).

Table 2. Effect of Pyrolysis Process Characteristics on Biochar

Production Method	**Temperature (°C)**	**Heating Rate**	**Main Product**	**Biochar Yield**
Slow Pyrolysis	350 - 650	Low	Biochar	High
Fast Pyrolysis	600 - 650	High	Bio-oil	Low
Gasification	> 700	High	Syngas	Very Low
Hydrothermal Carbonization HTC	180 - 250	Low	Hydrochar	Medium-High
Torrefaction	200 - 300	Low	Torrefied Biomass	Very High

Catalytic pyrolysis is a thermochemical conversion method that employs catalysts to enhance the yield and quality of specific products, such as fuels or high-value chemicals, during the pyrolysis process. These catalysts can also play a crucial role in the decomposition of tar compounds (tar cracking) formed during gasification. Furthermore, biochar itself can serve as a support material for catalytic reactions, such as the selective phenol hydrogenation of agricultural wastes (e.g., straw seed). To improve its catalytic performance, biochar can be transformed into engineered biochar through chemical or physical modifications, including doping with heteroatoms (N, S, P, B) or impregnation with metal/metal oxides (Fe, Co, Ni, Mn, Cu).

3. Sustainable Energy Applications

The intermittent and variable nature of renewable energy sources (e.g., solar, wind) necessitates the efficient storage of generated energy. Energy storage systems enhance grid stability by balancing energy supply and demand, thereby facilitating the broader integration of renewable energy. Sustainable energy storage technologies aim to minimize environmental impacts, ensure longevity, and maintain economic competitiveness. These technologies encompass electrochemical, thermal, mechanical, and chemical storage methods.

Biochar is emerging as a promising material, particularly within electrochemical energy storage systems (EES). EES devices are capable of directly converting chemical energy into electrical energy and storing it reversibly. The primary types of EES include:

- **Supercapacitors (Electrochemical Double-Layer Capacitors - EDLCs):** These devices offer high power density, rapid charge/discharge capabilities, and extended cycle life. They store energy through the physical accumulation of ions at the electrode-electrolyte interface, forming an electrochemical double layer (Kalla et al., 2024).
- **Batteries:** Characterized by high energy density, batteries store energy via chemical reactions (redox reactions) occurring at their electrodes. This category includes lithium-ion, sodium-ion, and metal-air batteries (Kalla et al., 2024; Liu et al., 2019).
- **Fuel Cells:** These systems continuously convert chemical energy (typically from a fuel like hydrogen) into electrical energy through electrochemical reactions, offering both storage and conversion functionalities (Liu et al., 2019).

Biochar's role in these systems typically involves its use as an active electrode material, a conductive additive, or a structural support. Its derivation from sustainable sources, low cost, and tunable properties render it an attractive alternative to fossil fuel-based carbon materials (e.g., activated carbon, carbon black) (Liu et al., 2019).

4. The Role of Biochar in Energy Storage Systems

As a sustainable and environmentally friendly material, biochar assumes diverse roles within energy storage systems. Its high surface area, tunable porous structure, favorable electrical conductivity, and chemical stability enable its application across a broad spectrum, ranging from supercapacitors to battery technologies, fuel cells, and gas storage systems (Kalla et al., 2024; Liu et al., 2019). With an increasing focus on sustainable and renewable energy sources, biochar-based materials have emerged as promising candidates for various energy-related applications (Chandrasekaran, Jadhav, Selvam, Krishnamoorthy, & Balasubramanian, 2024).

4.1. Supercapacitor Applications

Supercapacitors, also known as electrochemical double-layer capacitors (EDLCs), are energy storage devices characterized by high power density, rapid charge/discharge cycles, and extended cycle life. Biochar demonstrates significant potential as an active electrode material for these applications. The high surface area and optimized porous structure of biochar facilitate the swift adsorption and desorption of electrolyte ions onto the electrode surface, thereby enabling the achievement of high capacitance values (Kalla et al., 2024; Liu et al., 2019).

Research indicates that biochar derived from various biomass sources can exhibit electrochemical performance comparable to or even superior to that of activated carbon. For instance, biochars obtained from diverse biomass feedstocks have been successfully employed in supercapacitors, yielding capacitance values up to 1600 F/g and surface areas up to 340 m^2/g (Kalla et al., 2024). Further enhancements in supercapacitor performance can be achieved through heteroatom doping (e.g., with nitrogen or sulfur) and surface modifications, which improve biochar's wettability and conductivity (Liu et al., 2019).

4.2. Battery Technologies

Biochar-based materials are being investigated as both anode and cathode materials in various battery technologies. Its low cost, abundant availability, and inherent sustainability position it as an attractive alternative to conventional battery materials.

- **Sodium-Ion Batteries (SIBs):** Given the finite nature of lithium resources, sodium-ion batteries are considered a promising alternative. Biochar can provide a suitable carbon matrix for the storage of sodium ions. Optimized pore size distribution and surface functional groups support rapid sodium ion diffusion and stable cycling performance (Yu et al., 2023).

- **Lithium-Ion Batteries (LIBs):** Biochar can be utilized as an anode material in lithium-ion batteries. Specifically, biochars pyrolyzed at high temperatures can acquire graphite-like structural characteristics, making them suitable for lithium ion intercalation. The porous architecture of biochar can also contribute to extended cycle life by accommodating volume changes during cycling (Kalinke et al., 2021; Kalla et al., 2024).

- **Lithium-Sulfur Batteries (LSBs):** LSBs possess high theoretical energy density but face challenges such as the low conductivity of sulfur and the dissolution of polysulfides. Biochar can help overcome these issues by acting as a conductive matrix for sulfur and a scaffold capable of adsorbing polysulfides (Khandaker et al., 2025; Wang et al., 2023).

- **Solid-State Battery Applications:** Solid-state electrolytes offer safer and more stable batteries compared to their liquid counterparts. Biochar-based carbon materials can be employed as additives to enhance the conductivity of solid-state electrolytes or to stabilize the electrode/electrolyte interface (Raj, Perumal, Padhy, Rao, & Mohapatra, 2024).

4.3. Fuel Cell Applicaitons

Owing to its abundance and tunable surface chemistry, biochar is utilized as a catalyst or support material in fuel cells for electrochemical processes such as the oxygen reduction reaction (ORR) and hydrogen evolution reaction (HER), serving as a sustainable alternative to expensive commercial catalysts.

- **Microbial Fuel Cell (MFC) Electrode Development:** In MFCs, biochar can function as a bio-anode material, supporting microbial growth and facilitating electron transfer. The porous structure of biochar provides a large surface area for microorganisms and promotes biofilm formation (Logan, 2009).
- **Polymer Electrolyte Membrane Fuel Cell (PEMFC) Supports:** Platinum-based catalysts in PEMFCs are typically supported on carbon materials. Biochar can serve as a suitable support material for platinum nanoparticles. Its high surface area and corrosion resistance can enhance catalyst activity and longevity (Antolini, 2009).
- **Direct Carbon Fuel Cell (DCFC) Feedstock Applications:** DCFCs directly convert solid carbon fuels into electricity. Biochar can be used as a fuel in these cells, providing efficient energy conversion due to its high carbon content (Giddey, Badwal, Kulkarni, & Munnings, 2012).
- **Biochar-Based Electrocatalyst Synthesis:** Biochar can be employed as a precursor material in the synthesis of metal-free or metal-doped electrocatalysts for critical electrochemical reactions such as the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER). Doping with heteroatoms like nitrogen and sulfur significantly enhances catalytic activity (Zhang & Dai, 2015).

4.4. Hyrogen and Gas Storage Systems

The high porosity and surface area of biochar render it a potential adsorbent for the storage of hydrogen (H_2) and other gases (e.g., CO_2). Particularly under high pressure and low temperatures, the micropores of biochar can effectively trap gas molecules. Surface modifications and the formation of composites with metal-organic frameworks (MOFs) can further augment storage capacity (J.-R. Li, Kuppler, & Zhou, 2009).

4.5. Thermal Energy Storage

Biochar can be utilized as a support matrix for phase change materials (PCMs) in thermal energy storage systems. PCMs are capable of storing or releasing substantial amounts of thermal energy during melting and freezing. Thermal energy storage systems are often supported by renewable energy sources such as solar energy concentrating systems (Mehmet, PEKTEZEL, SIMSEK, & AKPINAR, 2025). Biochar's high thermal conductivity and stable structure can enhance the thermal cycling stability and heat transfer rate of PCMs (Sharma, Tyagi, Chen, & Buddhi, 2009).

4.6. Advanced Energy Storage Systems

Beyond conventional systems, biochar is also actively being investigated in next-generation energy storage technologies.

4.6.1. Metal – Air Batteries

Metal-air batteries (e.g., zinc-air, lithium-air) have garnered significant interest due to their high theoretical energy densities. Biochar can serve as a catalyst support material for the air electrode in these batteries. Its porous structure and active surface areas can catalyze oxygen reduction and oxygen evolution reactions, thereby improving battery performance (Y. Li & Lu, 2017).

4.6.2. Redox Flow Batteries

Redox flow batteries are promising systems for large-scale energy storage. Biochar-based carbon felts or electrode materials can provide the active surface area where redox reactions occur in these batteries. Surface modification of biochar can enhance electrode kinetics and overall battery efficiency (Weber et al., 2011).

4.6.3. Hybrid Photo-Electrochemical Systems

Hydrid photo-electrochemical systems can convert solar energy into electrical energy while simultaneously storing it. Biochar can be employed as a conductive and catalytic component for photoelectrodes or counter electrodes in these systems. The tunable optical and electronic properties of biochar hold the potential to enhance the efficiency of these systems (Walter et al., 2010).

5. Turkey's Waste Status and Current Potential

Turkey possesses a significant biomass waste potential owing to its rich biodiversity and extensive agricultural lands. These waste materials, through appropriate management and conversion processes, constitute a valuable resource for biochar production. The conversion of waste into biochar not only offers a sustainable solution to waste management challenges but also provides value-added materials for energy storage applications (Dursun, 2024).

Table 3. Turkey's Biomass Waste Resources and Biochar Production Potential

Waste Category	Total Waste Amount (ton/tear)	Energy Equivalent (TEP/year)	Biochar Potential (ton/year)
Agricultural Waste	46,990,000	19,260,200	11,747,500-16,446,500
Animal Waste	191,070,000	4,313,500	47,767,500-66,874,500
Municipal Organic Waste	32,170,975	3,373,011	8,042,744-11,259,841
Forest Waste	3,914,904 (stere)	859,899	978,726-1,370,216
TOTAL	**270,240,975**	**27,806,610**	**67,560,244-94,584,341**

5.1. Agricultural Wastes

Turkey, as a prominent nation in agricultural production, consequently generates substantial quantities of agricultural waste. These residues present a significant potential for biochar production.

Table 4. Biochar Potential from Agricultural Wastes in Turkey

Waste Category	Total Waste Amount (ton/year)	Energy Eşquivalent (TOE/year)	Biochar Potential (ton/year)
Agricultural Wastes	8,000 – 12,000	50,000 – 75,000	100,000 – 150,000
	2040	15,000,000 – 20,000,000	12,000 – 16,000

Figure 1. Waste amounts of the 12 agricultural products with the highest biochar potential in Turkey. Wheat straw (20 M ton/year) represents the largest potential by volume, while hazelnut shell (1.09 M ton/year) is the highest priority feedstock in terms of collectability and quality. Source: Republic of Turkey Ministry of Energy and Natural Resources, BEPA, 2024.

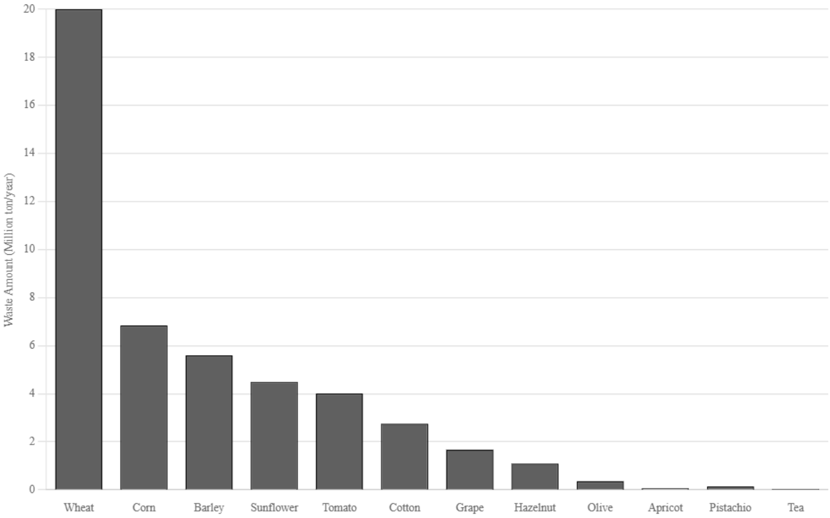

Figure 1. Agricultural Products with Highest Biochar Potential

5.1.1. Cereal Residues

Post-harvest stalks and stubble from cereals such as wheat, barley, and corn are abundantly available across Turkey's extensive agricultural lands. These residues, owing to their lignocellulosic composition, serve as suitable feedstocks for biochar production. According to the 2023 Agricultural Product Market Reports, cereal production in Turkey remains at high levels, signifying a substantial waste potential (Tarım ve Orman Bakanlığı, 2023).

5.1.2. Olive Processing Wastes

Turkey holds a significant position in global olive production. Olive pomace (pulp) and olive branches generated from olive processing facilities are ideal for biochar production due to their high organic matter content. Olive pomace, in particular, can also be utilized for energy recovery owing to its elevated oil content (Doymaz, 2011).

5.1.3. Hazelnut Processing Wastes

As Turkey accounts for a major portion of the world's hazelnut production, hazelnut shells constitute a significant agricultural waste stream. Hazelnut shells are highly suitable for producing high-quality biochar due to their high carbon content and rigid structure (TOPCU & DEMİRKESEN).

5.1.4. Tea Industry Wastes

Tea production, concentrated in the Black Sea Region, generates considerable amounts of tea stalks and leaf waste. These wastes can be valorized through biochar production, contributing to the regional economy (Müftüoğlu, Türkmen, & Kavdır, 2019).

5.1.5. Cotton Stalks

Cotton, extensively cultivated in the southern and southeastern regions of Turkey, leaves behind large quantities of stalk waste after harvest. Cotton stalks are viable for biochar production owing to their lignocellulosic nature (Bilek, Melikoğlu, & Cesur, 2019).

5.1.6. Garden and Vegetables Wastes

Widespread garden and vegetable farming across Turkey generates various wastes, including pruning residues, post-harvest plant remains, and spoiled vegetables. These wastes can be utilized for local-scale biochar production (Dursun, 2024; Erdem, İnce, Akyol, Özbayram, & İnce, 2015). A study by (Dursun, 2024) estimated the biochar potential from pruning wastes of fruit-bearing trees in Turkey to be 175 thousand tons for 2021. Apple trees were identified as having the highest biochar potential (41.5 thousand tons/year) (Dursun, 2024).

5.2. Forest and Wood Wastes

Turkey's extensive forested areas and robust timber industry provide a substantial feedstock source for biochar production.

5.2.1. Forest and Pruning Wastes

Branches, leaves, and other woody materials resulting from forest management, logging operations, and fire prevention efforts constitute forest wastes. These wastes can be utilized for biochar production while simultaneously mitigating the risk of forest fires (Ünlü, 2025).

5.2.2. Furniture and Timber Industry Wastes

Sawdust, wood chips, and cutting residues generated from furniture and timber production are ideal industrial wastes for biochar production due to their high carbon content and homogeneous composition (Şenkal, 2023).

5.3. Urban Solid Wastes and Organic Wastes

Organic wastes, which form a significant portion of the increasing urban solid waste stream due to urbanization, can be valorized through biochar technology.

5.3.1. Sewage Sludge

Sewage sludge from wastewater treatment plants contains substantial amounts of organic matter. Biochar produced from the pyrolysis of this sludge can both reduce sludge volume and immobilize heavy metals, thereby lowering environmental risks (Kabakcı & Koca, 2019).

5.3.2. Park, Garden and Landscape Wastes

Park, garden, and landscape wastes (e.g., grass clippings, pruned branches) collected by municipalities represent a sustainable urban biomass source for biochar production (Bilici & Karaer, 2024). Furthermore, the total biochar potential from pruning wastes of fruit-bearing trees in Turkey is estimated at 175 thousand tons for 2021 (Dursun, 2024).

- Apple trees: 41,5 thousand tons/year (highest potential)
- Apricot trees: 25,3 thousand tons/year
- Cherry trees: 32,1 thousand tons/year
- Peach trees: 27,2 thousand tons/year
- Plum trees: 66,0 thousand tons/yearıl
- Sour cherry trees: 30,4 thousand tons/year

5.3.3. Food Wastes

Household and commercial food wastes pose a significant waste management challenge in Turkey. Converting these wastes into biochar can help reduce methane emissions and contribute to a circular economy (Solak & Pekküçükşen, 2018).

5.4. Industrial Wastes

Organic wastes originating from various industrial processes can be utilized for biochar production.

5.4.1. Fruit Juice Factory Wastes

Pomace and peels remaining from fruit juice production are suitable feedstocks for biochar production due to their high organic matter content (Şener & Ünal, 2008).

5.4.2. Food Industry Wastes

Wastes from the general food industry (e.g., canning, baked goods) can be valorized through biochar production, thereby reducing waste management costs and yielding new products (Demirbaş, 2001).

5.4.3. Fish Factory Wastes

Wastes from fish processing facilities (e.g., bones, skin, offal) can be used to produce biochar rich in minerals such as phosphorus and calcium. This biochar can also be beneficial as an agricultural (Arvanitoyannis & Kassaveti, 2008).

5.4.4. Meat Industry Wastes

Wastes generated from meat processing facilities (e.g., bones, blood, fat) offer potential for producing specialized biochar types due to their high protein and mineral content (Jayathilakan, Sultana, Radhakrishna, & Bawa, 2012).

5.5. Animal Wastes

Turkey's developed livestock sector generates substantial amounts of animal manure waste. These wastes represent a valuable resource for biochar production. Animal wastes constitute the largest category of waste generated in Turkey.

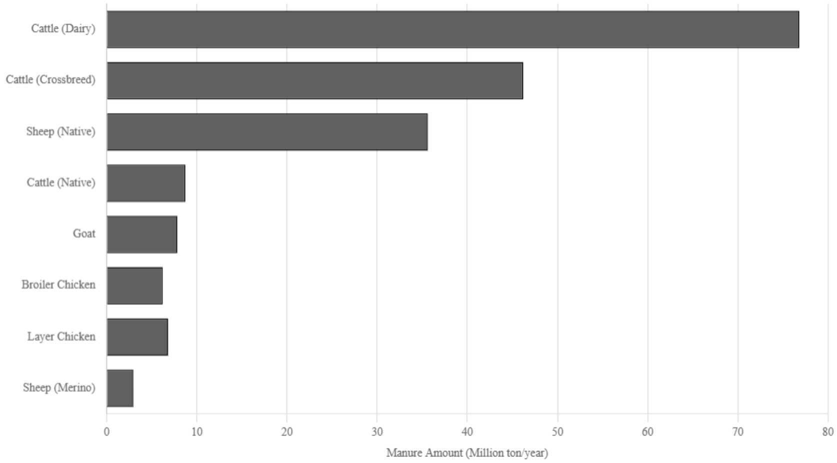

Figure 2. Biochar Potential from Animal Waste

Figure 2. Manure-based biochar potential of main livestock types in Turkey. Dairy cattle (76.8 M ton/year manure) represents the highest potential, while poultry (12.99 M ton/year) is particularly important for electrocatalyst applications due to high N-P content. Source: Republic of Turkey Ministry of Energy and Natural Resources, BEPA, 2024.

5.5.1. Poultry Manure

Poultry manure, characterized by its high nitrogen and phosphorus content, serves as a suitable feedstock for biochar production. The resulting biochar can also be effectively utilized as a soil amendment (Cantrell, Hunt, Uchimiya, Novak, & Ro, 2012).

5.5.2. Cattle and Small Ruminant Manure

Manure from cattle and small ruminants constitutes widely available biomass waste across Turkey. Converting these manures into biochar can contribute to reducing greenhouse gas emissions and recycling valuable nutrients (Dede,Dede, Dede, & Özdemir, 2018).

Turkey's rich waste potential presents a significant opportunity to support biochar production and, consequently, sustainable energy storage applications. The establishment of biochar production facilities optimized according to waste type and regional distribution will yield both environmental and economic benefits. If Turkey's total annual waste were directed towards biochar production, the estimated total biochar potential would be approximately 10.8 million tons (Kutlu & Kocar, 2017).

6. Biochar –Based Energy Storage Applications

Biochar's high carbon content, tunable porous structure, and natural abundance position it as a crucial raw material for sustainable energy storage solutions, particularly when compared to conventional fossil-based materials (Lonappan, Liu, Rouissi, Brar, & Surampalli, 2020). Turkey's substantial waste potential, in this context, offers significant opportunities.

6.1. Global Biochar Applications

Globally, biochar is extensively researched, especially in electrochemical energy storage systems such as supercapacitors and batteries. Studies indicate that biochar produced from diverse biomass sources (e.g., bamboo, rice husks, wood waste) exhibits promising electrochemical performance due to its high surface area and optimized porous structure (Kalla et al., 2024; Liu et al., 2019). For instance, some research has reported that biochar-based electrodes can achieve capacitance and energy density values comparable to, or even exceeding, those of commercial activated carbon electrodes (Khandaker et al., 2025).

Furthermore, the utilization of biochar as an anode or cathode material in lithium-ion, sodium-ion, and zinc-air batteries is becoming increasingly prevalent. Biochar's function as a conductive carbon matrix and its provision of active sites for ion storage enhance the performance of these batteries (Kalla et al., 2024; Liu et al., 2019). Additionally, innovative applications include the use of biochar as a support matrix for phase change materials in thermal energy storage systems and as a catalyst support in fuel cells (Kalla et al., 2024; Liu et al., 2019).

6.2. Turkey's Potential

Turkey possesses a rich potential in agricultural waste, forest waste, urban organic waste, and industrial biomass. The valorization of this potential for biochar production and its subsequent application in energy storage technologies holds immense environmental and economic significance.

- **Domestic and Sustainable Electrode Production:** Turkey's abundant waste resources enable the production of domestic and sustainable electrode materials for energy storage devices. This can reduce external dependency and contribute to national energy security.
- **Waste Management and Circular Economy:** Converting waste into biochar alleviates the burden on landfills, reduces greenhouse gas emissions, and offers a waste management model consistent with circular economy principles.
- **Regional Development:** The establishment of biochar production facilities, particularly in regions with intensive agriculture and forestry, can create local employment and foster regional development.
- **R&D and Innovation:** urkish universities and research institutions can conduct R&D activities focused on producing biochar with optimized properties from different waste types and enhancing its performance in energy storage systems. This will contribute to Turkey's technological advancement and competitiveness in this field internationally.

A study by (Dursun, 2024) highlights the substantial biochar potential derivable solely from pruning wastes. Fully evaluating this potential, including other waste types, will play a crucial role in Turkey's achievement of its sustainable energy goals.

Despite Turkey's high renewable energy potential, the capacity utilization rate for biomass energy remains low at 0.68% (Akusta & Cergibozan, 2020). This indicates an inadequacy in facilities and technologies required for converting biomass resources into energy (Akusta & Cergibozan, 2020). In this context, channeling idle biomass potential into biochar production will both mitigate waste management issues and provide domestic input for the energy storage sector (Gün & Balbay, 2025).

7. Future Outlook

The future of biochar in sustainable energy storage will be shaped by innovative research in materials science, engineering, and economics. Key areas expected to be the focus of future research include:

- **Customized Biochar Production:** The production of biochars with optimized porous structures, surface areas, and chemical properties from diverse biomass sources for specific energy storage applications (e.g., supercapacitors requiring high power or batteries demanding high energy density) is critically important. Precise control over production parameters (temperature, heating rate, catalyst usage) will be pivotal in achieving this objective.

- **Advanced Composite Materials:** Combining biochar with other functional materials such as graphene, carbon nanotubes, metal oxides, or conductive polymers to develop hybrid composite electrodes holds the potential to simultaneously increase energy and power density. These composites can offer superior performance by leveraging the synergistic effects of each component.

- **3D Printing and Flexible Devices:** The development of biochar-based inks could enable the fabrication of complex and customized electrode structures using 3D printing technology. Furthermore, integrating biochar into flexible polymer matrices will pave the way for the development of flexible supercapacitors and batteries for wearable electronic devices.

- **Life Cycle Analysis (LCA) and Economic Evaluation:** Comprehensive life cycle analyses (LCA) and techno-economic assessments are necessary to fully understand the environmental impacts and economic feasibility of biochar-based energy storage systems. These analyses will provide roadmaps for the commercialization of the technology.

- **Integration and System Optimization:** The integration of biochar-based energy storage units with renewable energy systems (solar panels, wind turbines) and the optimization of these integrated systems using mechanical engineering principles (e.g., thermal management, power electronics) will enhance efficiency and reliability. Advanced motion planning and path optimization algorithms, such as swarm robotics approaches (Yaşar, 2020), can be integrated into automated biochar production and material handling systems to improve operational efficiency and reduce energy consumption.

8. Conclusion and Recommendations

This book chapter has elucidated the multifaceted role and potential of biochar as a sustainable resource in energy storage applications. Biochar is an environmentally friendly, low-cost, and tunable carbon material that can be produced from abundant and diverse biomass wastes. It offers promising results across a wide range of applications, including supercapacitors, batteries, fuel cells, and thermal energy storage systems.

Turkey, with its rich agricultural, forest, and urban waste potential, is strategically positioned for biochar production and its utilization in energy storage technologies. Harnessing this potential will significantly contribute to the country's sustainable energy goals, address waste management challenges, and facilitate a transition to a circular economy model.

To accelerate progress in this field, the following recommendations are put forth:

1. **Development of a National Biochar Strategy:** A comprehensive national biochar strategy should be formulated, mapping Turkey's waste potential, identifying priority regions and waste types, and promoting R&D activities and commercial production.

2. **Support for R&D and Innovation:** Projects focusing on the production of high-performance biochar from different waste types and its application in energy storage devices should be supported through collaboration among universities, research centers, and the private sector.

3. **Establishment of Pilot Facilities:** Pilot-scale biochar production and energy storage system integration facilities, based on local waste resources, should be established in various regions to demonstrate the technology's feasibility and scalability.

4. **Interdisciplinary Collaboration:** Interdisciplinary collaboration among mechanical engineers, chemical engineers, materials

scientists, and environmental scientists should be encouraged to address all processes, from the design to the production and optimization of biochar-based energy storage systems, with a holistic approach.

5. **Technology Transfer and Localization:** Internalizing biomass conversion technologies (pyrolysis, gasification) within Turkey and supporting the use of domestic components are crucial for reducing foreign dependency in the energy sector and building export capacity.

In conclusion, biochar stands as an exciting and transformative material with significant potential at the intersection of mechanical engineering and sustainable energy. Realizing this potential will be a crucial step towards a cleaner, safer, and more sustainable energy future.

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