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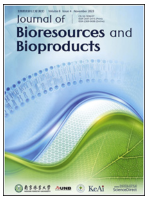

Review

An overview of biomass solid fuels: Biomass sources, processing methods, and morphological and microstructural properties

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ABSTRACT

Biomass solid fuel (BSF) has emerged as a promising renewable energy source, but its morphological and microstructural properties are crucial in determining their physical, mechanical, and chemical characteristics. This paper provides an overview of recent research on BSF. The focus is on biomass sources, BSF processing methods, and morphological and microstructural properties, with a special emphasis on energy-related studies. Specific inclusion and exclusion criteria were established for the study to ensure relevance. The inclusion criteria encompassed studies about BSFs and studies investigating the influence of biomass sources and processing methods on the morphological and microstructural properties of solid fuels within the past five years. Various technologies for converting biomass into usable energy were discussed, including gasification, torrefaction, carbonization, hydrothermal carbonization (HTC), and pyrolysis. Each has advantages and disadvantages in energy performance, techno-economics, and climate impact. Gasification is efficient but requires high investment. Pyrolysis produces bio-oil, char, and gases based on feedstock availability. Carbonization generates low-cost biochar for solid fuels and carbon sequestration applications. Torrefaction increases energy density for co-firing with coal. HTC processes wet biomass efficiently with lower energy input. Thermal treatment affects BSF durability and strength, often leading to less durability due to voids and gaps between particles. Hydrothermal carbonization alters surface morphology, creating cavities, pores, and distinctive shapes. Slow pyrolysis generates biochar with better morphological properties, while fast pyrolysis yields biochar with lower porosity and surface area. Wood constitutes 67% of the biomass sources utilized for bioenergy generation, followed by wood residues (5%), agro-residues (4%), municipal solid wastes (3%), energy crops (3%), livestock wastes (3%), and forest residues (1%). Each source has advantages and drawbacks, such as availability, cost, environmental impact, and suitability for specific regions and energy requirements. This review is valuable for energy professionals, researchers, and policymakers interested in biomass solid fuel.

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1. Introduction

Implementation of a renewable energy policy is fundamental to reducing the global dependence on fossil fuels and their products (Mahbub et al., 2019). Fossil fuels are tending to extinction and contribute considerably to global warming (Ibitoye et al., 2021a; Krishna Koundinya et al., 2023). Governments and non-government agencies worldwide are developing and implementing guidelines and incentives to encourage the adoption of renewable energy strategies, including tax credits, subsidies, and mandates for energy producers to utilize a given proportion of renewable energy in their energy combination (Stevens et al., 2023; Syed et al., 2023).

Renewable energy is an energy source that can be replenished over a short period. Examples include geothermal, solar, hydro, wind, and biomass (Ibitoye et al., 2021b; Tilahun et al., 2021; Khare et al., 2022). These energy sources are considered sustainable and clean alternatives to conventional fossil fuels. This is because they release negligible or less greenhouse gas (GHG) and other pollutants contributing to air pollution and climate change. Renewable energy technologies have grown significantly in recent decades, becoming more cost-effective and efficient (Uddin et al., 2019; Gaurav et al., 2020). For instance, solar photovoltaic panels are now more efficient and affordable, making them a common choice for commercial and residential use (Irfan et al., 2023). Likewise, wind turbines have grown more dependable and can generate electricity in low-wind situations (Maheshwari et al., 2023). Also, biomass feedstock generates gas, solid, and liquid fuels for different applications (Fang et al., 2020).

Biomass solid fuels (BSFs), such as briquettes and pellets, are manufactured from compressed biomass feedstock, including agricultural residues, sawdust, and forest waste. These materials are compacted with or without any binders at high pressure, resulting in a product with higher energy and apparent density than raw biomass (García et al., 2020). These solid fuels are comparable in size and shape to coal briquettes and traditional charcoal. They can be used for cooking, heating, and other energy applications (Yoo et al., 2019). The BSFs offer many advantages over conventional fossil fuels, such as crude oil and coal. They are produced from organic materials or residues that would have been burned or disposed of and cause GHG emissions and air pollution. The BSFs have a lesser carbon footprint than fossil fuels and can help minimize non-renewable energy product utilization (Heredia Salgado et al., 2020; San Miguel et al., 2022). Moreover, BSF can be manufactured locally, which supports local economies and can create jobs.

The materials used for the production of BSFs can be gathered from different sources, including forest residues (Prasad and Raturi, 2021), energy crops (Králík et al., 2023; Manić et al., 2023), agricultural residues (Silva-Martínez et al., 2020), domestic wastes (Hai et al., 2023), municipal waste (Olatunji et al., 2022), etc. The choice of biomass source can significantly impact the characteristics of BSF. Biomass chemical compositions differ by type, affecting combustion properties and energy content. For instance, lignocellulose biomass, such as agricultural residues and sawdust, has a high cellulose content, which makes them a promising feedstock for solid fuel production (Rajput et al., 2020). A study has shown that fuels made from forest feedstock had lower ash content and higher calorific value than those made from agricultural residues (Casas-Ledón et al., 2019). This is because forest biomass has higher cellulose content than agricultural residues.

For many developing countries, especially those in Africa, obtaining affordable, reliable energy remains a serious problem (Bamisile et al., 2023). The current electrical infrastructure frequently falls short, is unstable, and can not keep up with expanding businesses and population growth needs (Murshed and Ozturk, 2023). Electricity shortages affect various industries, including healthcare, education, agriculture, and business. The quality of life of many people is impacted by the lack of energy, which hinders social advancement and economic growth. The research and progress of biomass energy stand out as a practical answer in light of this ongoing problem (Bamisile et al., 2023; Lin and Okyere, 2023). Supplying disadvantaged populations with dependable and reasonably priced power from biomass might close the electricity gap (Monyai, 2023). Also, decentralized systems and biomass-based mini-grids can increase access to energy in rural areas, creating new possibilities for socio-economic growth (Monyai, 2023; Wiredu et al., 2023). The advancement of biomass energy also supports international initiatives to address climate change (Okorie and Lin, 2022; Bamisile et al., 2023).

Biomass feedstock undergoes several processes to generate solid fuel for different applications. The popular processing methods are mechanical, thermal, and biological (Ajimotokan et al., 2019; Somorin et al., 2020; Ibitoye et al., 2021c, 2022; Zhang et al., 2023a). The common mechanical processing method involves compressing the biomass material using compaction forces without binders (Sharma and Dubey, 2020). However, other processing methods, such as adjusting the moisture content of feedstock or using binders, can also be used to improve the properties of solid fuels (Sermyagina et al., 2022). The processing techniques adopted to produce BSFs can also influence their properties (Xing et al., 2019; Ríos-Badrán et al., 2020). The BSFs made through a combination of binders and biomass usually display better mechanical properties and higher calorific value than non-composite BSFs without any binding agent (Sharma and Dubey, 2020). The thermal processing methods involve heating biomass feedstock in an inert atmosphere (Varma et al., 2019; Ibitoye et al., 2023a). This process improves the heating, combustion, and water resistance properties of the resulting solid fuels (Sharma and Dubey, 2020; Guo et al., 2022a). Thermal treatment processes include carbonization (Wang et al., 2022), torrefaction (Kolapkar et al., 2022; Ibitoye et al., 2023b), pyrolysis (Glushkov et al., 2021), gasification (Aydin et al., 2019), etc., and differences in operating temperature characterize these processes.

According to the research of Afolabi et al. (2020), BSFs have a range of morphological and microstructural properties that can influence the combustion efficiency, strength, reactivity, and emissions of BSFs. Morphological and microstructural properties include specific surface area, grain size, and shape, porosity, surface morphology, crystal structure, grain structure, the morphology of phases, amorphous structure, nanoscale morphology, surface roughness, etc. (Falk et al., 2019; Nazimudheen et al., 2021; Kieush et al., 2022). Understanding the impact of biomass sources and processing methods on these properties is essential for optimizing the production and use of BSFs as renewable energy sources. Several research efforts have been put into developing BSFs from different biomass sources and utilizing different processing methods (Mitchual, 2014; Zhai et al., 2018; Rajput et al., 2020). Also, many investigations have been conducted on the morphological and microstructural properties of BSFs (Pegoretti Leite de Souza et al., 2021; Zha et al., 2022). However, a recent comprehensive overview of the identification of biomass sources and the impact of processing methods on the morphological and microstructural properties of biomass BSFs is yet to be conducted. Therefore, this article reviews the recent research and development on BSF using articles available on the ScienceDirect database. The present review innovatively offers a comprehensive and in-depth analysis of various aspects related to biomass-based solid fuels. It includes details about biomass sources, densification techniques, thermal treatment technologies, and morphological and microstructural properties. It also emphasizes the significance of taking into consideration environmental implications and sustainability. This multifaceted and comprehensive approach distinguishes it from earlier reviews that may have concentrated on individual features of BSFs.

2. Review methodology

A comprehensive search strategy was developed to identify relevant studies for the review process. This strategy involves searching the ScienceDirect database for BSFs-related studies. The search strategy includes using the following keywords and combinations: biomass briquettes, biomass pellets, renewable energy, biomass sources, biomass processing methods, biomass morphological properties, biomass microstructural properties, particle size distribution, density, porosity, carbonization, moisture content, ash content, binders, densification additives, biomass torrefaction, biomass pyrolysis, and biomass carbonization. On the other hand, to provide reliable sources for some information presented in this review, details related to the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) were obtained from the official website of the organization. Information on ASTM and ISO standards was obtained from https://www.astm.org and https://www.iso.org, respectively. The criteria for inclusion and exclusion of studies were developed based on the subject of the review (Vlachokostas et al., 2021; Balali et al., 2023). The inclusion criteria include studies published in peer-reviewed journals, studies conducted on BSFs, studies that identified potential biomass sources, and papers that investigate the impact of processing methods on the properties of BSFs. Exclusion criteria include investigations that do not meet the inclusion criteria, papers that are not written in English, manuscripts that are not available in full text, and studies that were not carried out in the last five years. However, some data from ASTM and ISO cited in the manuscript represents the latest version available. It should be noted that ASTM and ISO citations later than 2019 have not been updated in the last five years.

The specific subject of the review was used to develop data extraction and analysis methods. Identifying relevant information from the included studies, such as the used type of biomass, the employed processing methods, and the properties of the resulting BSFs, is involved in data extraction (Balali et al., 2023). The review and analysis involve synthesizing the data from the included studies and identifying patterns and trends in the findings and discussion. To guarantee transparency and rigor in the review process, established guidelines such as the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines are followed to ensure the quality and validity of the review (Araújo et al., 2020).

3. Biomass source

This section identified and discussed potential sources of biomass feedstock for energy production. The sources identified and discussed include wood and wood residues, food waste, animal and livestock wastes, agricultural and forest residues, municipal solid wastes, and energy crops. Fig. 1 shows the share of biomass sources in bioenergy combination.

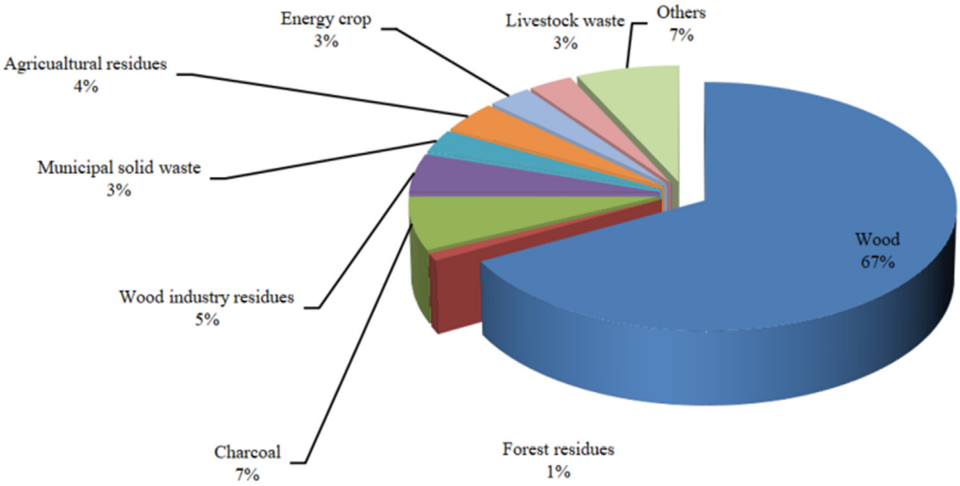

Fig. 1. Percentage of biomass sources in bioenergy combination (Food and Agriculture Organization of the United Nations, 2022; The Intergovernmental Panel on Climate Change, 2022).

3.1. Wood and wood residue

Wood and wood residues are potential sources of biomass feedstock for energy production. For many decades, wood has been the primary source of energy for humankind, and today wood is still among the most extensively utilized renewable and sustainable energy sources in the world (Mu et al., 2023; Saravanakumar et al., 2023). Wood residues are generated in huge quantities by the wood processing and forestry industries. Using wood and wood residue for energy generation has several advantages: they are widely available in the worldwide and are renewable (Fahmy et al., 2021). Unlike conventional energy sources such as fossil fuels, wood waste and wood biomass are replenishable *via* waste reduction plans and justifiable forest control practices. Furthermore, using wood residues and wood for energy production lower the global carbon footprint than conventional energy (Kuznetsov et al., 2022). Combustion of woody biomass releases CO_2 into the atmosphere, but this CO_2 is offset by the CO_2 absorbed by the trees and plants during their growth (How et al., 2019; Baral et al., 2021). In addition, using woody biomass for energy production prevents the wood residues/wastes from going to landfills, which can result in the emission of GHG.

The simplicity of using wood biomass boosted its utilization for domestic cooking and heating. It can be burned directly in simple stoves or open flames for heating and cooking. Since only a minimal amount of infrastructure is required to burn wood as fuel, it is advantageous in places with little access to advanced energy sources. Wood produces much heat when appropriately burned, making high-temperature applications possible quickly. Many technologies have been developed to convert wood biomass and residues into usable energy, including gasification, torrefaction, carbonization, and pyrolysis (Singh et al., 2020). Each transformation technique has merits and demerits regarding efficiency, costs, and emissions.

Possible weaknesses exist in utilizing wood biomasses and residues for energy production. These include a tendency for loss of biodiversity and deforestation (Uddin et al., 2019). If forest wood is collected at a rate more rapidly than it can be regenerated, it can result in deforestation, erosion, and destruction of territories of many species. Consequently, it is crucial to ensure that wood biomass is generated sustainably, considering the philosophies of ecological forestry, including conserving biodiversity, protecting soil and forest, and water quality (Eltigani et al., 2022). Fig. 2 depicts the link between direct biomass combustion and other modern bioenergy sources, according to Food and Agriculture Organization of the United Nations (2022). The graph shows that the use of biomass through direct combustion decreases over time while the use of solid fuels created by advanced technology increases.

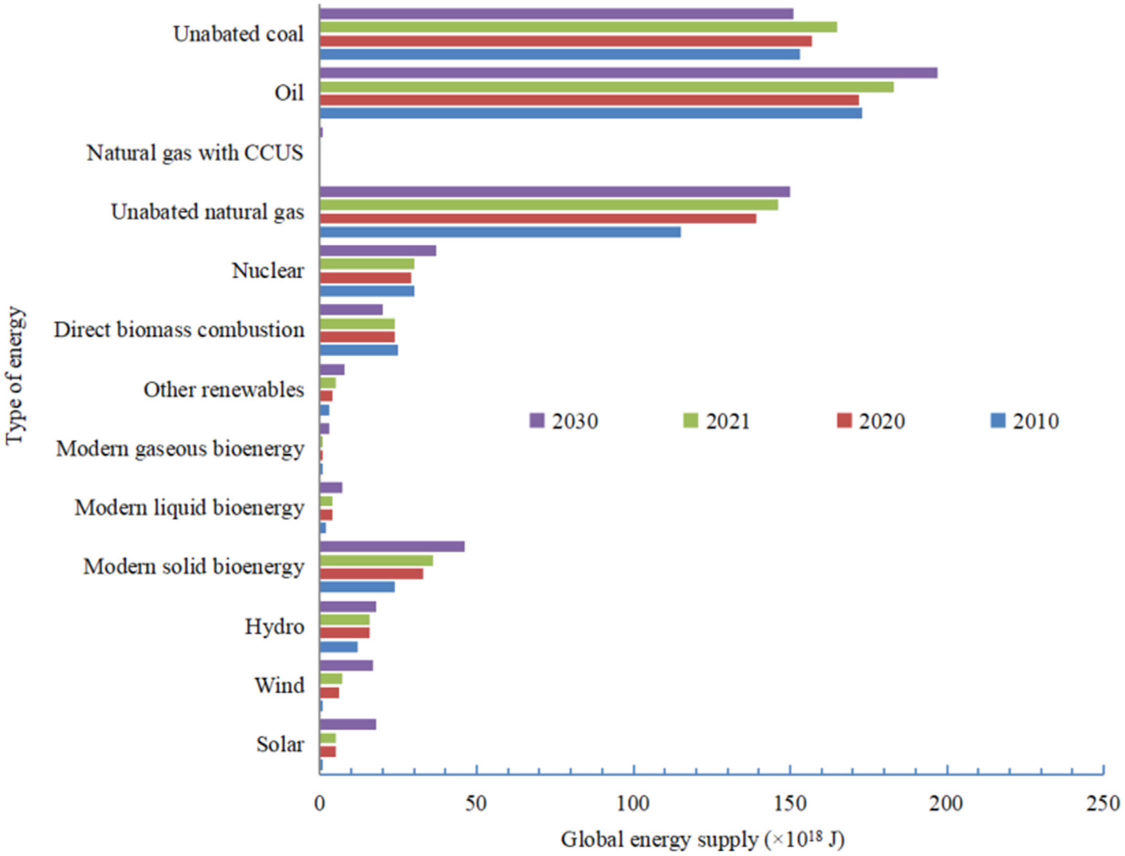

Fig. 2. Comparison of direct biomass combustion to other modern bioenergy (2010–2030) (Food and Agriculture Organization of the United Nations, 2022).

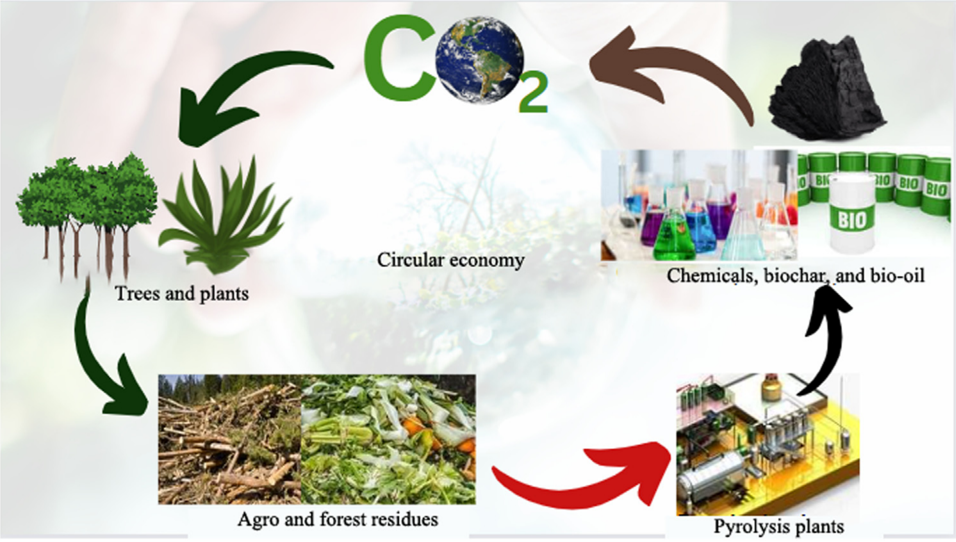

Fig. 3. Conversion of forest and agricultural residues to useful energy and circular economy.

According to Fig. 2, solid fuels produced using modern processing technologies are more promising than solar, wind, hydro, liquid, and gaseous bioenergy.

Another apprehension is the possibility of air pollution from burning wood and wood residues. While using wood can be regarded as a relatively environmentally friendly energy source, if wood combustion is not done in an up-to-date boiler or stove, it can also generate harmful substances such as particulate matter (fine particles and soot are emitted during wood burning), carbon monoxide, nitrogen oxides, volatile organic compounds (organic chemicals that evaporated into the atmosphere), etc. (Vershinina et al., 2019; Rabha, 2021).

The finances of wood biomass utilization require critical analysis. The transportation and collection of forest wood and residue for energy production can be quite costly and entail substantial investments in infrastructure. This is because the cost of transporting and producing wood biomass varied generally based on the forest location and wood type technology adopted in processing wood (Casas-Ledón et al., 2019). In addition, the price of wood and wood residues as feedstock for energy production can be influenced by competition with other sources of energy, such as solar, wind, natural gas, coal, etc. (Casas-Ledón et al., 2019). It is the responsibility of everybody to work towards a more ecologically friendly and socially responsible energy future by balancing the social factors contributing to the popularity of wood and the requirement for sustainable energy practices.

Fig. 3 depicts the conversion of wood and agricultural residues to useful energy and the development of a circular economy. Converting forest and agricultural residue in a circular economy is desirable for long-term sustainability. However, logistic difficulty, other land-use requirements, technological constraints, profitability, environmental impact, governmental bottlenecks, and public perception all challenge its implementation (How et al., 2019; Awasthi et al., 2020). Overcoming these challenges will necessitate joint efforts and a change toward recognizing the lasting advantages of sustainable practices.

3.2. Food waste

Another source of biomass feedstock for energy production is food waste. Food wastes are all kinds of organic materials discarded during food processing, eating, and production (Chen et al., 2023; Hai et al., 2023). Food waste can be collected from grocery stores, restaurants, households, and other food-associated industries. The primary merits of utilizing food waste as a feedstock for energy production include its advanced domestic and industrial waste management technique and reduction of GHG emissions (Siaw et al., 2022). Anaerobic decomposition occurs when food waste is thrown in an open field or left to degrade in a landfill. Anaerobic decomposition occurs in the absence of oxygen and produces methane (CH_4), a potential GHG that contributes considerably to climate change (Le et al., 2022). Methane is more effective than carbon dioxide at trapping heat in the atmosphere. While methane has a far lower atmospheric concentration than carbon dioxide, its impact on global warming is still significant due to its greater heat-trapping capabilities (Lahiri et al., 2023). On the other hand, using food waste for energy generation can counterbalance the emissions from conventional energy sources and minimize the global carbon footprint of the food industry (Siaw et al., 2022). Furthermore, using food waste for energy can create jobs and provide extra revenue streams for the people. Many towns and cities are implementing and promoting food waste-to-energy initiatives, such as biogas for cooking, electricity generation, livestock feed, and beddings, digestate for fertilizer and soil amendment etc., which create fresh prospects for energy and waste management industries.

Considerable know-how can be adopted to transform food waste into sustainable energy. Examples include composting, fermentation, hydrothermal carbonization, and anaerobic digestion (Feiz et al., 2022; Le et al., 2022). A typical process that breaks down organic matter in the absence of oxygen to generate gas is known as anaerobic digestion (Fig. 4) (Feiz et al., 2022). The produced

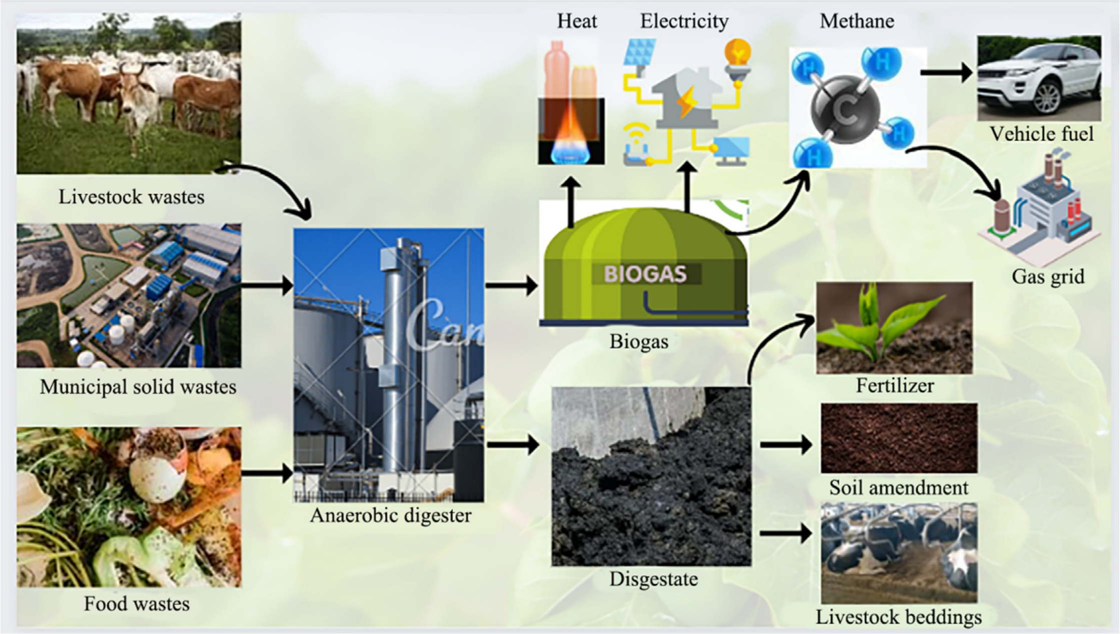

Fig. 4. Anaerobic digestion of biomass feedstock and its application.

gas (biogas) can generate heat and electricity. Similarly, the natural breakdown of organic material to generate a soil amendment rich in nutrients is called composting (Mohanakrishna et al., 2023). There are also several possible drawbacks to utilizing food waste for energy production. The major worry is the potential for rivalry with food production. Generating large amounts of food waste for energy production could result in food scarcity and decrease soil productiveness because organic matter is not returned to the soil for nutrient generation (Lahiri et al., 2023). Further, huge food waste generation is a source of environmental pollution. Also, the gathering, processing, and transporting of food waste could increase GHG emissions if not efficiently done.

3.3. *Animal/Livestock waste*

Livestock wastes, also called animal wastes, are a promising source of biomass feedstock for renewable energy production. Livestock waste includes urine, manure, and every organic material generated by livestock (Zhong et al., 2020). Using animal wastes for energy production can enhance waste management and minimize GHG emissions. Most of the time, livestock waste is dumped in pits, open filed, or lagoons. Discarded animal waste decomposes and releases methane, a GHG that causes climate change (Shirzad et al., 2019). However, converting animal waste into useable energy can offset emissions, enhance a sustainable environment and reduce GHG release in the agricultural sector. Using animal waste for energy production can provide an extra source of income for farmers and people living in remote communities. Several farmers and people living in remote communities have less access to financial and energy opportunities; therefore, converting their livestock waste into fuel for energy production would provide additional income for them. All the biomass conversion methods, merit, and demerit associated with the generation of energy from food wastes discussed in Section 3.2 also apply to livestock wastes.

3.4. *Agricultural residues*

Agricultural residues include all branches of crops that remain after the harvest and agro-product processing. Agricultural residues are leaves, stems, shells, stalks, husks, straws, and other parts associated with agricultural products (Uddin et al., 2019; Bareschino et al., 2021). An abundant supply of feedstock for renewable energy production is agro-residues. The characteristics of agro-residues greatly depend on several factors: farm location, soil composition, crop type, and weather conditions (Silva-Martínez et al., 2020). For instance, rice husk and straw are popular agro-residues in places where large quantities of rice are cultivated, likewise, maize cob and stalks. The characteristics of agro-residues can be influenced by the post-harvest processing method and the age or stage of plant growth before harvest.

Globally, several billion metric tons of agro-residues are generated annually (Avcıoğlu et al., 2019). The utilization of agro-residues as a biomass source has several benefits. These include cost-effectiveness, reduced GHG emissions, minimizing environmental pollution, employment creation, etc. (Zhang et al., 2021a). Furthermore, agricultural residues offer other benefits, such as soil improvement, animal feed, and use as building materials. Agro-residues can also be used in fiber, paper, and textile production (How et al., 2019; Králík et al., 2023).

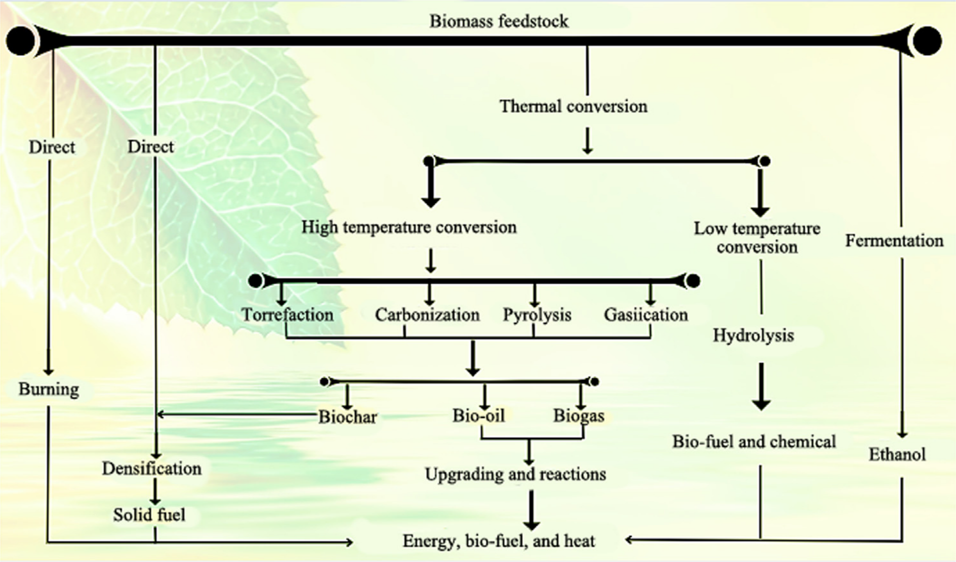

Fig. 5. Biomass conversion technique.

Even though the use of agro-residues for energy production provides many benefits, there are some limitations and drawbacks connected to their use. The quantity of residues generated greatly depends on crop yield. Collection, transportation, storage, etc., are factors limiting agro-residue use for renewable energy generation. This is due to their low bulk density, making handling agricultural residues difficult (Brigagão et al., 2019; Brand and Jacinto, 2020). Other limiting factors include low thermal and combustion efficiency, low heating value, poor flowability, and high hygroscopic (Okolie et al., 2020; Guo et al., 2022a). However, several technologies have been developed to mitigate the challenges, including densification, thermal pretreatment, biochemical conversion, and anaerobic digestion (Zhong et al., 2020; Martínez-Guido et al., 2021; Awasthi et al., 2022). The choice of technology adopted depends on the desired end-use and type of agro-residue. The densification, direct, and thermal conversion process of biomass feedstock into usable energy is shown in Fig. 5.

3.5. *Forest residues*

Forest residues are portions of trees that remain after logging or sawmilling processes. It includes tops, branches, bark, dust, and chips from forest wood processing activities. Forest residues are a renewable source of biomass feedstock for energy generation (Vitale et al., 2022; Dudziec et al., 2023). Studies have revealed that forest residues are generated in enormous quantities worldwide (Casas-Ledón et al., 2019; Stafford et al., 2020). They are available in abundance, especially in remote areas. The elemental constituent and quantity of forest residues available for energy generation depend on the type of forest tree, harvesting methods, age, weather conditions, region, harvest period and forest management practices adopted in the region (Casas-Ledón et al., 2019; Stafford et al., 2020; Balcioglu et al., 2023). Forest residues can significantly mitigate climate change by reducing it by more than 80 % compared to energy derived from fossil fuels (Balcioglu et al., 2023). Utilization of forest residues can save approximately 7.3 million metric tons of carbon dioxide equivalent and 0.5 billion dollars annually (Balcioglu et al., 2023).

3.6. *Municipal solid waste*

Another promising source of feedstock for energy production is municipal solid waste (MSW). The MSW is waste generated by businesses, organizations, households, offices, research institutes, educational institutions, etc. The MSW includes paper, food scraps, metals, biomass, plastics, and other related feedstock (Santos and Hanak, 2022; Nasiri et al., 2023). The use of MSW for energy production can minimize environmental pollution resulting from the disposal of this waste in open fields, landfills, and open fire burning that could lead to climate change (Santos and Hanak, 2022). Additionally, MSW is an inexpensive source of biomass feedstock for energy production, particularly if the production site is located close to urban centers where enormous MSW is generated. Another benefit of MSW as a sustainable source of feedstock for energy production is that it can provide a steady and dependable energy source compared to other biomass types, which availability depends on the climatic condition and related factors (Santos and Hanak, 2022). The primary concern of generating energy from MSW is the possibility of liberating air pollutants, specifically if the conversion (processing) method is not properly and efficiently managed. Moreover, there are challenges associated with logistics, including collection, handling, and transportation (Zhang et al., 2023b). Therefore, using MSW as a feedstock for energy production must be cautiously evaluated to guarantee that it is the best, most economical, and sustainable choice for energy production and waste management technique (Santos & Hanak, 2022).

3.7. Energy crops

The global energy demand has resulted in the need to seek alternative sources, and energy crops are among the possible sources. The crops cultivated primarily for energy production are regarded as energy crops (Anejionu and Woods, 2019; Knápek et al., 2021). These crops are cultivated to reduce the over-dependence on conventional energy and increase the generation of renewable energy from biomass of high energy potential. There are many kinds of energy crops, such as woody, annual, and perennial (Albers et al., 2020; Schwerz et al., 2020; Králík et al., 2023). Annual crops are cultivated and harvested within one year. Annual crops can generate quality biogas, biochar, and bio-oil, which can be burned directly for energy application. Maize, sorghum, and sugar beet are prominent annual crops (Albers et al., 2020). Studies have shown that annual crops are the most appropriate for ethanol production, which can serve as an alternative to gasoline. On the other hand, perennial crops are usually cultivated and grown for many years (Králík et al., 2023). They grow very fast, and most of the time, high yields are recorded from their cultivation. In addition, perennial crops offer environmental advantages, including carbon sequestration and soil conservation. Miscanthus, willow, and switchgrass are popular perennial crops (Schwerz et al., 2020). When perennial crops are properly processed by adopting appropriate methods, they can generate electricity or heat for domestic and industrial applications. Woody crops are shrubs and trees cultivated and developed for wood use and energy application (Schwerz et al., 2020). Examples of woody crops are poplar, eucalyptus, and willow. Woody crops are utilized as biomass feedstock for renewable energy generation. These include transformation into gaseous, solid, and liquid biofuels and direct combustion. Through pyrolysis and gasification, woody crops can be converted into gaseous biofuels that may be utilized as fuel or converted into valuable compounds (Aydin et al., 2019; Mu et al., 2023). It may also be used as solid biofuels for heat and power generation (Ibitoye et al., 2023c), processed into liquid biofuels such as bioethanol for transportation fuel (Nazimudheen et al., 2021).

Energy crops present many advantages. The cultivation of energy crops can lead to the advancement of rural communities. It can create jobs and income for the people, minimize carbon footprint, enhance soil nutrients, and encourage biodiversity (Vamvuka et al., 2023). Energy crops serve as promising biomass feedstock for renewable energy generation, which can be used as an alternative and supplement to fossil fuels. It can enhance the availability and accessibility of energy to people in rural areas. Energy crops can be cultivated on borderline or boundary lands, which are inappropriate for the cultivation of food crops, thus enhancing efficient land use. Boosting employment in rural areas is achieved through the significant labor required for cultivating, harvesting, and processing energy crops (Sahoo et al., 2022). Compared to fossil fuels, energy crops have a lower carbon footprint. Mitigating climate change and reducing GHG emissions is possible by producing and using energy crops. Switchgrass and miscanthus, which are perennial energy crops, have been proven to enhance soil fertility, increase soil organic matter, and reduce erosion, thereby improving soil health (Chen et al., 2019; Zheng et al., 2019; Králík et al., 2023). Ensuring the sustainability of energy crop production is crucial.

Even with the advantage associated with the cultivation of energy crops, there are several challenges related to their use for different energy purposes. These include rivalry for land use, cost, labor requirement, etc. (Sahoo et al., 2022). The cultivation of energy crops competes with traditional food crops and land practices, including urbanization, food production, forestry, and environmental sustainability policies. The cultivation of energy crops requires a large volume of water, which can lead to rivalry for water resources, especially in areas where access to water is very poor (Králík et al., 2023). Furthermore, cultivating energy crops may necessitate using pesticides, fertilizers, etc., which may cause soil degradation and environmental pollution. The production of energy crops needs substantial land, equipment, technology, and infrastructure investments. Also, the commercial success of energy crop generation depends on government policies (Sahoo et al., 2022).

A comprehensive approach is required to address the challenges associated with energy crops for bioenergy production. This includes promoting sustainable land use and planning, which enables prioritizing energy generation without competing with valuable agricultural land or essential ecosystems (Dumortier et al., 2020; Králík et al., 2023). Also, encouragement of different types of energy crop developments, use of non-food biomass sources, and exploration of marginal lands may reduce the impact on food crops and enhance sustainability (Knápek et al., 2021). Water-efficient energy crops and precision irrigation techniques can help optimize water utilization and reduce strain on water resources. Integrated pest management practices can reduce the use of pesticides and fertilizers, hence reducing environmental damage (Anejionu and Woods, 2019). Government support through incentives and legislation can stimulate the adoption of environmentally friendly sustainable energy crops (Knápek et al., 2021). Involving local people in decision-making can help resolve land use problems while ensuring socio-economic well-being. In addition, circular economy techniques and life cycle analysis can maximize energy crop utilization while evaluating environmental implications and directing ecologically friendly practices (Schmidt Rivera et al., 2020). It is possible to balance bioenergy production, environmental conservation, and social well-being by collectively implementing these solutions for a sustainable energy future.

4. The BSFs processing methods

The BSFs are a sustainable, environmentally friendly, and renewable energy source manufactured from different biomass feedstock by adopting several processing methods. Various methods of processing biomass materials into solid fuels (briquettes or pellets) exist. Each method has merits and demerits and suitability for different applications. The popular BSFs processing methods include the stamping press, piston press, hydraulic press, extrusion, roll press, carbonization, pyrolysis, torrefaction, and hydrothermal carbonization (Matkowski et al., 2020; da Silva Alves et al., 2021; Zaini et al., 2021; Tabakaev et al., 2022). Fig. 6 depicts the different processes of generating biomass solid fuels.

The mechanical stamping press, extrusion, and roll press are ideal for large-scale production of BSF (da Silva Alves et al., 2021; Tabakaev et al., 2022), while the piston press and hydraulic press are more suitable for small-scale production (Matkowski et al.,

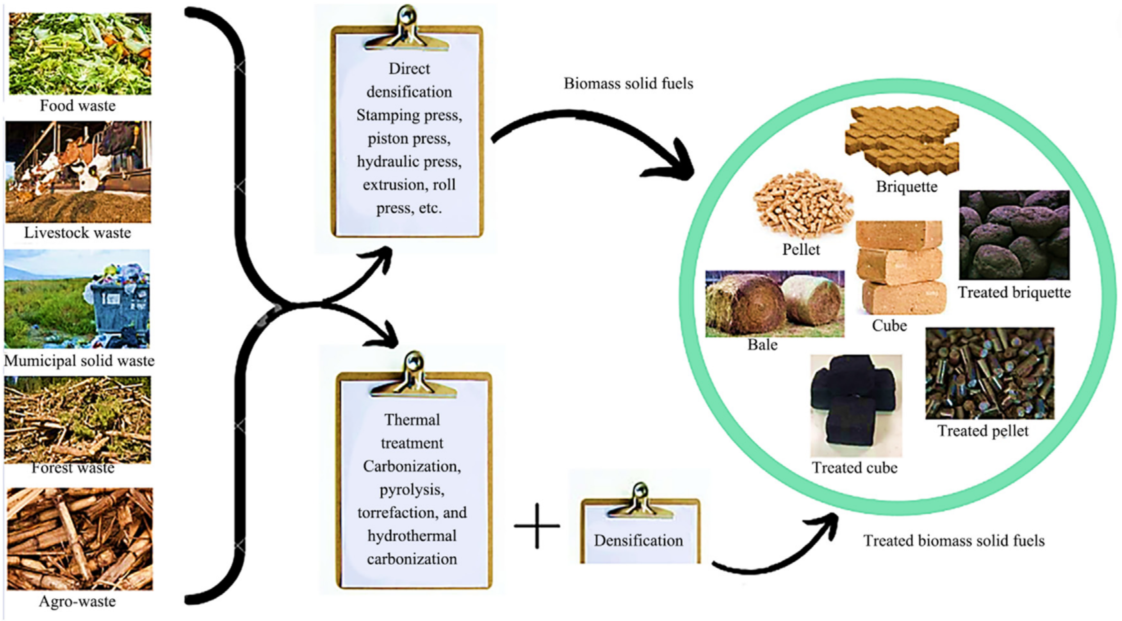

Fig. 6. Biomass solid fuels and processing methods.

2020; Zaini et al., 2021). Carbonization and pyrolysis can produce high-energy content fuels but require high energy input and can produce toxic byproducts. Lignin bonding and binder additives can improve the bonding properties of low-quality biomass materials (Zaini et al., 2021; Guo et al., 2022a). At the same time, torrefaction and hydrothermal carbonization can be used to process wet and low-quality biomass materials (Aragón-Briceño et al., 2021; Guo et al., 2022a; Kolapkar et al., 2022). The choice of processing method depends on the availability and characteristics of the biomass materials, the desired quality of the BSFs, and the scale of production. The description, merit, demerit, and application of different biomass processing methods are presented in Table 1. The ranking of BSFs according to their energy density and a comparison with other solid fuels is presented in Table 2.

5. Morphological and microstructural property

In this section, the morphological and microstructural properties of BSFs are discussed.

5.1. Morphological property

Morphology refers to the study of the structure (size, shape, etc.) and form of materials at larger scales, including macroscopic scales. This includes analyzing and understanding the physical and chemical characteristics of materials and their behavior and properties under different conditions (Khiari et al., 2019; Yu et al., 2022a). Morphology property is essential in engineering and materials science because morphology and inner structure often characterize the behavior or properties of materials. For instance, the ductility, durability, and strength of a material may be influenced by the orientation of its crystal lattice, grain size, particle size distribution, and particle shape (Caicedo-Zuñiga et al., 2022; Kieush et al., 2022).

The morphological characteristics of BSFs describe the physical properties connected to the form and structure of the BSFs. These properties are essential for determining and assessing the physical arrangement, visual appearance, handling and logistic characteristics, combustion efficiency, strength, and storage properties of BSFs (Nazimudheen et al., 2021). It is crucial to investigate morphological properties when assessing the performance and quality of BSFs.

Several analytical approaches are used to study the morphology property of BSFs, including spectroscopy (del Pozo et al., 2021), microscopy (Jelonek et al., 2020), scattering (Krishna Koundinya et al., 2023), and diffraction (Kwoczynski and Cmelík, 2021). Scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FT-IR), X-ray diffraction (XRD), and Raman spectroscopy are prominent spectroscopic techniques used to analyze the morphology and characteristics of biomass solid fuels. The SEM produces high-resolution surface images, allowing particle size and form to be examined. The TEM has a better resolution and can investigate ultrastructures at the nanoscale level. The FT-IR analysis the crystallographic structure and molecular vibrations, whereas XRD and Raman spectroscopy analyze the chemical composition and functional groups. These techniques enable investigators to analyze and visualize feedstock structure at diverse length scales, from the atomic to the macroscopic level. By having an in-depth understanding of the morphology characteristics of BSFs, energy specialists can optimize and design solid fuels for energy applications. This includes improving the durability, strength, and other related materials properties that enhance BSFs for energy production. Examples and descriptions of the morphological property of BSFs are presented in Table 3.

Table 1
Description, merit, demerit, and application of various biomass processing methods.

Item	Processing method	Description	Merits	Demerits	Applications	Refs.
Binding process	Binder additive	It involves adding a binding agent to biomass feedstock to improve their bonding characteristics during the densification process.	It can produce fuels with high strength and uniform shape and is ppropriate for making solid fuels from low-quality biomass feedstock.	It may require pre-processing of biomass materials. The use of specific binders can have negative environmental impacts.	Suitable for making briquettes from low-quality biomass feedstock (such as sawdust, straw, and paper waste) that does not have sufficient natural binding agents	Dai et al. (2019), Riva et al. (2019a), Rajput et al. (2020), Shui et al. (2020), Sermyagina et al. (2022)
	Lignin bonding	It involves using lignin, a natural binding agent in biomass, to compress and form solid fuels.	It uses a natural binding agent and can produce briquettes with high density and strength.	Limited availability of lignin in some biomass feedstock may result in lower-quality briquettes if not properly processed.	Suitable for making solid fuels from biomass materials with high lignin content	Cao et al. (2020), Sharma and Dubey (2020), Zhang et al. (2020a), Guo et al. (2022a), Nasiri et al. (2023)
Thermal process	Carbonization	It involves heating biomass materials (180–250 °C) in an inert environment to produce biochar (charcoal), which is then compressed into solid fuels.	The process produces high-energy content solid fuels with low moisture content, which is suitable for the production of BSFs long-term storage and improve hydrophobic properties of BSF.	The process requires high temperature and energy input. It can produce toxic byproducts.	Suitable for making charcoal solid fuels from wood residues and other high carbon content biomass materials	Plaza et al. (2019), Qin et al. (2022), Yeletsky et al. (2022), Zhang et al. (2023a)
	Torrefaction	It involves heating biomass materials (200–300 °C) at a low temperature to remove moisture and volatile compounds.	It can produce solid fuels with high-energy content and improved combustion characteristicsand. It is suitable for the production of BSFs for long-term storage and can improve the water resistance property of solid fuels.	It requires high temperature and energy input. It can produce toxic byproducts.	Suitable for making solid fuels from low-quality biomass materials such as agricultural wastes and forest residues	Kung and Ghoniem (2019), Dhaundiyal et al. (2021), Awasthi et al. (2022), Chen et al. (2022), Soria-Verdugo et al. (2022), Szufa et al. (2023)
	Pyrolysis	It involves heating biomass materials (300–900 °C) in the absence of oxygen to produce liquid bio-oil, gas, and char.	It can produce different types of biofuels in addition to solid fuels—high energy output.	It requires high temperature and energy input. It can produce toxic byproducts. It can be expensive.	Suitable for making BSFs and other biofuels from high-energy content biomass materials, such as wood chips and sawdust.	del Pozo et al. (2021), Zaini et al. (2021), Gvozdyakov et al. (2022), Mumbach et al. (2022), Koulouri et al. (2023)
	Hydrothermal carbonization	It involves heating biomass feedstock (180–300 °C) in water at high pressure to produce hydrochar, which is then compressed into solid fuels.	It can produce high-energy content solid fuels with low moisture content and is suitable for long-term storage of BSFs.	It can produce toxic byproducts. It can be expensive. It requires high temperature and energy input.	Suitable for making solid fuels from wet and low-quality biomass materials such as sewage sludge and manure	Medina-Martos et al. (2020), Román et al. (2020), Zhang et al. (2020b), Aragón-Briceño et al. (2021), Zhang et al. (2021b)

(*continued on next page*)

Table 1 (*continued*)

Item	Processing method	Description	Merits	Demerits	Applications	Refs.
Mechanical process	Piston press	It involves compacting biomass feedstock using a piston press to form solid fuels.	It can produce briquettes/pellets with high density and uniform shape and is suitable for small-scale solid fuel production.	It requires electricity to operate, has low production rate and high initial investment cost.	Appropriate for small-scale production of BSFs from agricultural wastes, forestry residues, and other biomass materials	García et al. (2020), Matkowski et al. (2020), Tumuluru et al. (2020), Berghel et al. (2022)
	Extrusion	It involves compressing the biomass feedstock through a die using an extruder to form solid fuels.	It is suitable for continuous production and can manufacture solid fuel with high density and uniform shape.	It has high initial investment cost and requires electricity to operate.	Suitable for continuous production of solid fuels from forestry residues, agricultural wastes, and other biomass feedstock	Manouchehrinejad et al. (2021), Kolapkar et al. (2022), Tabakaev et al. (2022)
	Roll press	Comprises compacting biomass materials using a roll press to form solid fuel	It is suitable for large-scale production and can manufacture solid fuels with uniform shapes and high density.	It may require pre-processing of biomass feedstock, has high start-up cost, and requires electricity to operate.	Suitable for large-scale production of solid fuels from agricultural and forestry residues and other biomass materials	Aydin et al. (2019), Setter et al. (2020), Dhaundiyal et al. (2021), Mumbach et al. (2022)
	Pellet mill	It involves compressing biomass materials through a die using a pellet mill to form pellets.	It is suitable for long-distance transportation and storage and can manufacture pellets with high density and uniform shape.	It requires electricity to operate and a high initial investment cost. It may require pre-processing of biomass feedstock.	Suitable for making pellets from a wide range of biomass materials, such as sawdust, agricultural wastes, and forestry residues	Shui et al. (2020), Surup et al. (2020), Zawiślak et al. (2020)
	Hydraulic press	It involves compressing biomass feedstock using a hydraulic press to form briquettes/pellets.	It can generate briquettes with high density and uniform shape. It is usually adopted for small-scale production.	It has high initial investment cost and rquires electricity to operate. It may require pre-processing of biomass materials.	Suitable for small-scale production of briquettes from agricultural wastes, forestry residues, and other biomass materials	Riva et al. (2019a), Sharma and Dubey (2020), Zaini et al. (2021), Orisaleye et al. (2022)
	Screw press	It involves compacting biomass feedstock into the press, which is compressed by a rotating screw and forced through a tapered die to form briquettes or pellets.	It is suitable for small to medium-scale production. It is energy-efficient and requires minimal electricity to operate. It can process a wide range of biomass materials and produce briquettes or pellets with high density and uniform shape.	The screw press can be prone to wear and tear and may require frequent maintenance. It may require pre-processing of biomass materials. The final product may have lower density and strength compared to solid fuels produced by other methods. The screw press is not suitable for large-scale production.	It is suitable for small to medium-scale production of solid fuels from agricultural residues, sawdust, and other biomass feedstock. It is also suitable for households and small businesses looking to produce solid fuel for cooking or heating purposes.	Michelangelli and Covas (2014), Fang et al. (2020), Orisaleye et al. (2020)

Note: BSF, biomass solid fuel.

Table 2
Ranking of BSFs according to their energy density.

Rank	Biomass solid fuels	Energy density $(\times 10^{9}\ \mathrm{J/m^{3}})$	Comparison with other fuels	Refs.
1	Cotton stalk hydrochar*	25.46–38.05	Similar to coal	Cao et al. (2020)
2	**Hydrochar	24.60–26.40	Similar to coal	Wang et al. (2020)
3	*Rice husk char	18.99–23.09	Similar to Wood Chips	Hu et al. (2015)
4	Extracted spruce sawdust*	22.84	Similar to coal, higher than firewood	Sermyagina et al. (2022)
5	Torrefied wood*	16–22	Similar to coal, higher than firewood	Shui et al. (2020)
6	Cotton stalk*	20.89	Similar to torrefied biomass pellets	Cao et al. (2020)
7	Wood sawdust*	18.60	Similar to agricultural residues	Wang et al. (2020)
8	Spruce sawdust*	16.54	Similar to agricultural residues	Sermyagina et al. (2022)
9	Torrefied pine, blended with solid (raw pine and grape pomace) *	12.18–15.33	Higher than regular wood pellets	García et al. (2020), Albashabsheh and Heier (2021)
10	Coffee husk*	13.19	Similar to wood chips	Setter et al. (2020)
11	Eucalyptus nitens*	11.79	Similar to wood chips	Pegoretti Leite de Souza et al. (2021)
12	Eucalyptus wood*	11.60	Similar to wood chips	Jesus et al. (2020)
13	Blends of elephant grass, sugarcane bagasse, and eucalyptus wood*	8–11	Similar to wood chips	da Silva et al. (2020)
14	Pinus radiata*	10.81	Similar to wood pellets	Pegoretti Leite de Souza et al. (2021)
15	Paulownia elongata X fortune*	10.00	Similar to wood pellets	Pegoretti Leite de Souza et al. (2021)
16	Miscanthus X giganteus*	9.98	Similar to wood pellets	Pegoretti Leite de Souza et al. (2021)
17	Biomass***	7.30–7.99	Similar to wood Pellets	Albashabsheh and Heier (2021)
18	Torrefied rubber wood sawdust*	4.94–6.59	Higher than regular wood pellets	Kongto et al. (2021)
19	Biomass**	6.40	Similar to wood pellets	Albashabsheh and Heier (2021)

Notes: *refers to the pellet
** refers to the briquette
*** refers to the cube.

5.2. Microstructure property

From an engineering and materials science perspective, microstructure properties display the internal structure or characteristics of a material at the microscale level. It comprises the size, shape, arrangement, and spread of the constituent phases of a material (Gaurav et al., 2020; Odeyemi et al., 2020). Microstructure properties of material include crystals, grains, phases, and other microstructural characteristics such as inclusions, cracks, and pores (Sahu et al., 2022; Tagami-Kanada et al., 2022). Microstructural properties determination or investigation is a crucial aspect of biomass solid fuel characterization, as it facilitates the development of solid fuel with enhanced properties and performance. Understanding the microstructure properties of BSFs helps optimize, design, and manufacture processes to attain desired attributes and increase solid fuel performance for various energy applications.

Microstructure property plays an essential and dominant role in assessing the physical, mechanical, and chemical characteristics of BSFs (Odeyemi et al., 2020; Yu et al., 2022a). The mechanical characteristics of solid fuels, such as strength, durability, impact resistance, drop to fracture, and toughness, greatly depend on the microstructural properties of the solid fuel (Odeyemi et al., 2020; Yu et al., 2022b). For instance, defects, such as voids, inclusions, and dislocations, can weaken a solid fuel. Furthermore, particle size, particle shape, and grain distribution can also affect the durability and strength properties of solid fuels (da Silva et al., 2020).

The microstructure property of BSFs can be determined or investigated using various techniques mentioned in the last paragraph of Section 5.2, including XRD, microscopy, and electron diffraction (Ong et al., 2021; Kieush et al., 2022). Examples and descriptions of the microstructural properties of BSFs are presented in Table 3.

5.3. Interconnection between morphological and microstructural properties of BSFs

The study of morphological and microstructural properties of BSFs is critical to understand the behavior and properties of solid fuels and is essential for biomass fuel design, processing, and optimization (Ong et al., 2021). Depending on the context, some of the properties of BSFs can be classified as morphological and microstructural. Such properties include the morphology of phases, amorphous structure, nanoscale, and surface morphology (Gong et al., 2022; Abdullah et al., 2023). These properties involve both morphological aspects, focusing on the shape, size, and arrangement of components, and microstructural aspects, considering the internal structure and characteristics of the material at a microscopic level (Kieush et al., 2022; Le et al., 2022; Zha et al., 2022).

Morphology of phases, amorphous structure, and nanoscale morphology can be considered morphology properties. Morphology of phases refers to the shape or form of individual phases within a biomass material, observed on the surface or in a cross-section of the biomass material (Gong et al., 2022). For example, if a biomass material contains multiple phases, such as different crystal structures, the morphology of each phase can be observed by examining the external shape and form of the individual crystals (Husain et al., 2022). The morphology characteristic resulting from the lack of long-range order structure in a material or a cross-section of the biomass material is amorphous (Lisowski et al., 2019; Gong et al., 2022). An amorphous material can be differentiated from a

Table 3
Morphological and microstructural properties of biomass and BSF.

Item,	Properties	Description	Implication/effect	Standard method	Equipment/technique	Refs.
Morphological property	Surface area	It refers to the total area of the external surfaces of the biomass particles or solid fuel per unit mass or volume. It represents the surfaces of biomass or BSFs exposed to the surrounding environment.	It affects fuel reactivity, catalytic activity, and other surface-related properties.	ASTM D3663-03; ASTM B923-21; ISO 9277	AFM and gas adsorption (BET analysis)	Kung and Ghoniem (2019), Santos et al. (2020), Sitek et al. (2021), Abdullah et al. (2023)
	Color	It refers to the hue, saturation, and brightness of the briquette.	It affects marketability and consumer perception. It can indicate the degree of charring or treatment during thermal processing, providing information about the energy content and combustion behavior of the material.	ASTM D2244-16; ASTM E308-17; ISO 11664-4	Spectrophotometer, colorimeter; visual inspection	Brazil et al. (2019), Riva et al. (2019a), Jelonek et al. (2020), del Pozo et al. (2021)
	Grain shape	It refers to the form or outline of the BSFs, such as cylindrical, rectangular, or spherical.	It affects handling, combustion behavior, and transportation.	Visual inspection; ASTM E112; ASTME930; ISO 643	Ruler; caliper	Riva et al., 2019b; Odeyemi et al., 2020; Ríos-Badrán et al., 2020; Sermyagina et al., 2022; Yu et al., 2022a; Saravanakumar et al., 2023
	Morphology of phases*	It refers to the shape, size, and distribution of different phases in a material.	It can influence thermal and combustion properties.	ASTM E45-18; ASTM E112-13; ISO 643; ISO 14104	SEM; optical microscopy;TEM; XRD	Koesoemadinata et al. (2021), Guo et al. (2022b); Kieush et al. (2022), Yeletsky et al. (2022)
	Amorphous structure*	It refers to the absence of long-range order in a material.	It influences fuel properties, such as mechanical strength and transparency.	ASTM D3418-15; ASTM D5017-19; ISO 5803	TEM; XRD; DSC	Khiari et al. (2019), Somorin et al. (2020), Erses Yay et al. (2021)
	Nanoscale morphology*	The structure and properties of materials on the nanometer scale, which can be different from those on the macroscopic scale	It can control biomass properties.	ASTM E2456-06; ASTM E2490-11; ASTM E2859-11; ISO 11979-5; ISO 9276-6	TEM; SPM; SAXS; SANS	Falk et al. (2019), Khiari et al. (2019)
	Surface roughness	It is a measure of the texture of a surface and is typically characterized by the height and spacing of the surface features, such as peaks and valleys.	Optical and mechanical properties	ASTM E2847-21; ASTM E177-19; ISO 4287; ISO 25178-2	Stylus profilometers; optical profilometers; confocal microscopy; AFM; white light interferometry; laser scanning confocal microscopy	Mu et al. (2023)

(*continued on next page*)

Table 3 (*continued*)

Item,	Properties	Description	Implication/effect	Standard method	Equipment/technique	Refs.
Microstructural	Grain size	The size of individual grains or crystals within a material	Mechanical properties and behavior of the material	ASTM E112; ASTME930; ISO 643	SEM; TEM; EBSD; XRD	Trubetskaya et al. (2020), Kolapkar et al. (2022), Yeletsky et al. (2022)
	Phase composition	The types and amounts of different phases present in a material	Properties and behavior of a material	ASTM E415; ASTM E1085; ISO 12677	XRD; EDS; XRF; SEM	Kung and Ghoniem (2019), Kieush et al. (2022), Kolapkar et al. (2022), Sermyagina et al. (2022)
	Texture	The spatial arrangement and orientation of grains or crystals within a material	Mechanical properties and behavior	ASTME82/ 82M; ISO 16603	EBSD; SEM; XRD	Rajput et al. (2020), Kieush et al. (2022), Yeletsky et al. (2022)
	Inclusions	The presence and size of foreign particles or phases within a material	Properties and behavior of a material	ASTM E45; ASTM E1245; ISO 4967	SEM; TEM; XRD; EDS	Heredia Salgado et al. (2020), Jelonek et al. (2020)
	Surface morphology*	The shape and size of the surface features or topography of a material	Properties and behavior of a material	ASTM E112-13; ASTM E1382-97; ISO 25178	SEM; AFM; contact profilometry; optical microscopy	Kolapkar et al. (2022), Wang et al. (2022), Lebiocka et al. (2023)
	Crystal structure	The arrangement of atoms in a material	Determines its properties and behavior under different conditions	ASTM E1382-97; ASTM E915-21	SEM; XRD; ED; TEM; EBSD	Erses Yay et al. (2021), Wang et al. (2022)
	Grain structure	The size, distribution, and orientation of grains in a polycrystalline material	It affects its mechanical properties, such as strength and ductility.	ASTM E112-13; ASTM E930-09; ASTM E1181-02; ISO 643	Optical microscopy; SEM; TEM; EBSD	Riva et al. (2019a), Cao et al. (2020), Jelonek et al. (2020), Rajput et al. (2020), Kieush et al. (2022)
	Defects	Imperfections in material and BSF, such as vacancies, dislocations, and grain boundaries	It affects properties such as heating, combustion, and mechanical strength.	ASTM E45-18; ASTM E112-13; ASTM E381-20; ISO 643; ISO 10675-1	Raman spectroscopy; STEM; XRD; PAS	Khiari et al. (2019), Setter et al. (2020), Yeletsky et al. (2022)
	Porosity	The amount and size of pores or voids in a material	It influences heat, combustion, and mechanical characteristics of BSFs.	ASTM E228-20; ASTM E837-13; ISO 22854	Mercury porosimetry; gas adsorption (BET analysis); X-ray computed tomography	Riva et al. (2019b), Surup et al. (2020), Yeletsky et al. (2022), Abdullah et al. (2023), Zhang et al. (2023a)

Notes: *, it can be classified as morphology and microstructural property depending on context. AFM, atomic force microscopy; SANS, small-angle neutron scattering; SAXS, small-angle X-ray scattering; SEM, scanning electron microscopy; SPM, scanning probe microscopy; BET, Brunauer–Emmett–Teller; DSC, differential scanning calorimetry; EBSD, electron backscatter diffraction; ED, electron diffraction; EDS, energy-dispersive X-ray spectroscopy; PAS, photoacoustic spectroscopy; TEM, transmission electron microscopy; XRD, X-ray diffraction; XRF, X-ray fluorescence; STEM, scanning transmission electron microscope.

crystalline material by its absence of well-defined crystal faces and edges in its morphology (Gong et al., 2022). The organization and dimensions of nanoscale characteristics inside a substance are what is regarded as nanoscale morphology (Ong et al., 2021).

Conversely, amorphous structure, nanoscale morphology, and morphology of phases can also be well-thought-out as microstructure properties of BSF because they relate to the internal structure of a material at the microscale level (Ong et al., 2021; Kieush et al., 2022). The morphology of phases can be studied on a microscopic level, within crystals or individual grains in a biomass material. The form and shape of every crystal or grain can influence the thermal and mechanical characteristics of solid fuels (Husain et al., 2022). For example, a polycrystalline material with an elongated grain can display anisotropic mechanical characteristics, whereas a material with randomly shaped particles can show isotropic mechanical characteristics (Kieush et al., 2022). The arrangement of nanoparticles within a larger structure can influence the characteristics of the resulting material (Husain et al., 2022). This is because the arrangement of nanoparticles affects how particles interact. The amorphous structure of biomass material is a microstructural property that defines the lack of long-range order structure (Lisowski et al., 2019; Gong et al., 2022).

Some morphological and microstructural properties of BSFs that are important for energy application are presented in Table 3. These properties are essential in understanding and designing BSFs for various energy applications. The techniques and equipment used to determine microstructural and morphology properties of biomass feedstock and BSFs can vary depending on the specific property being measured.

6. Techno-economic performance of biomass processing methods

Investigating the techno-economic (TE) performance of biomass processing methods for renewable energy generation is crucial in determining the practicality and profitability of using biomass as a renewable energy source (Salimbeni et al., 2023; Saravanan et al., 2023a). Biomass use in energy generation must be thoroughly assessed to guarantee that it is economically feasible and environmentally sustainable. Therefore, papers related to the economic and environmental performance of biomass and biomass processing methods in comparison with other sustainable and climate-neutral technologies are discussed in this section.

6.1. Feedstock procurement, operating costs and efficiency

The TE analysis assesses several components of the biomass supply chain, from feedstock acquisition to final energy utilization (Makepa et al., 2023). A study explored the potential of new vehicle technologies for biomass feedstock supply, considering their impacts on biofuel production (Baral et al., 2021). Butanol was a typical biofuel in comprehensive TE and life-cycle studies for diesel, fuel cell hybrid electric, and fully electric trucks. The findings reveal that fuel cell hybrid electric and fully electric trucks use less energy with lower cost and carbon footprints, especially when traveling long distances.

The cost of getting biomass feedstock is another crucial aspect of the TE analysis (Patil et al., 2023; Saravanan et al., 2023b). Biomass feedstock availability and accessibility vary greatly depending on geographical regions and indigenous agricultural and forestry practices (Duc Bui et al., 2023). Feedstock costs may be comparatively inexpensive in places with significant agricultural and forest activities, making biomass energy economically beneficial. Feedstock prices may be higher in places where biomass is scarce or has different applications (e.g., as food or animal feed), affecting the general financial viability of biomass energy projects.

An investigation on the TE analysis of two torrefaction and pelletization systems for producing torrefied wood pellets (torrefaction before pelletization and torrefaction after pelletization) revealed that feedstock cost and torrefaction yield were the most sensitive parameters that influence the TE performance of energy generated *via* biomass processing methods (Manouchehrinejad et al., 2021; Makepa et al. 2023). Also, Prasad and Raturi (2021) quantified forest logging residue in Fiji and evaluated the TE and environmental assessment for a 10 MW biomass power plant. The project shows promising results with a net present value of 16.1 million dollars, a simple payback period of about five years, and a benefit-to-cost ratio of 2.5, considering a feedstock cost of 68.6 dollar per tonne and an electricity export tariff of 0.1621 dollar per kW·h. Critical factors affecting the project viability include electricity export tariff, power plant availability, and feedstock costs.

Operating cost is another essential aspect of the TE biomass assessment for energy generation (Makepa et al., 2023; Real Guimarães et al., 2023). Labor, maintenance, logistics, and energy use during biomass processing are all included in these costs. The operational costs can be influenced by the effectiveness of the processing methods and the scope of operations (Liu et al., 2022; Naveen et al., 2023). The efficiency of converting biomass into valuable energy is a significant element in the TE study (Ma et al., 2021; Yu et al., 2023). High conversion efficiencies translate to more energy output per biomass-treated unit (Farajollahi and Hossainpour, 2023; Weyand et al., 2023). Biomass may be converted into various energy types, including electricity, heat, and biofuels, each having its conversion efficiency. A TE analysis of the thermochemical conversion of corncob-to-energy has been conducted (Brigagão et al., 2019). Three corncob-to-energy pathways were evaluated. Fast pyrolysis, biomass gasification, and combustion achieve 79%, 53%, and 30.2 % net efficiency, respectively. Analysis of the results showed that all pathways were economically viable provided the biomass costs are below 75.5 dollar/t. For economic characteristics, the lowest possible product costs are 305 dollar/t, 80.1 dollar/(MW·h), and 1.47 dollar per gallon-equivalent for methanol, electricity, and bio-oil, respectively (Brigagão et al., 2019).

Another study evaluated the TE feasibility of sorption-enhanced gasification, a waste-to-fuel process with *in-situ* CO_2 capture. It was assessed against typical MSW steam gasification for hydrogen production (Santos and Hanak, 2022). Sorption-enhanced gasification achieved higher hydrogen production efficiency (48.7 %) than conventional gasification (47.7 %). The economic analysis revealed that sorption-enhanced gasification resulted in a higher equivalent hydrogen cost than conventional gasification.

Medina-Martos et al. (2020) compared integrating hydrothermal carbonization and anaerobic digestion to standalone anaerobic digestion. It was discovered that the integrated approach reduces environmental impacts through hydrochar recovery and improves energy efficiency by 14 %. However, the economic concerns require further optimization as the hydrothermal option was 42 % costlier than conventional anaerobic digestion. Nonetheless, hydrothermal treatments offer a potentially sustainable route for sewage sludge treatment, particularly for nutrient and energy recovery.

6.2. Environmental impact of biomass processing methods

The environmental impact of biomass processing methods is a vital component of the TE analysis, in addition to economic concerns. Biomass energy is often regarded as renewable and carbon-neutral because the CO_2 emitted during combustion is countered by the CO_2 utilized by plants during growth. However, subject to the biomass and combustion technology employed, biomass energy can still produce GHG and other pollutants throughout the combustion process (Real Guimarães et al., 2023; Patil et al., 2023). As a result, assessing the ecological effects of biomass energy production and comparing it to other sustainable and climate-neutral technologies is critical. When comparing biomass processing methods to environmentally friendly and climate-neutral technologies such as solar, wind, or geothermal energy, several factors must be considered, a comprehensive assessment of the environmental implications, resource availability, and technological efficiency (Ma et al., 2021; Ruiz et al., 2023).

Various forest-related bioenergy know-how for switching to a low-carbon economy in Quebec, Canada, were evaluated by Kouchaki-Penchah et al (2022). Detailed modeling using a TE approach was performed, and the pathways were implemented in a bottom-up energy model. Results showed that the transportation sector is a primary GHG contributor. It was added that extensive electrification and increased bioenergy usage could help achieve reduction targets. The report further showed that forest-based bioenergy like cellulosic bioethanol, bio-based heat, Fischer-Tropsch diesel, etc., can effectively support the energy transition and contribute to decarbonization (Kouchaki-Penchah et al., 2022).

The TE performance and environmental aspects of the anaerobic digestion process on a city scale were performed (Chen et al., 2023). Results showed that renewable natural gas from food waste could offset a significant portion of natural gas usage in various sectors, such as residential, commercial, industrial, and transportation. The considered pathways, except for pipeline natural gas, are economically viable. Additionally, all pathways result in negative GHG emissions, making anaerobic digestion more eco-friendly for food waste handling than landfills (Chen et al., 2023). Similarly, a comparison between biomass and natural gas-fuelled boilers for residential thermal energy demands in a cold Italian climate revealed that the boiler fed by tobacco chips offers environmental and economic benefits over the traditional system, significantly reducing CO_2 emissions. A simple payback period of about five years and a net present value of 17,168 yuan (EUR) (without economic support) was also reported (Bareschino et al., 2021).

A pilot-scale system that combines torrefaction and extrusion to convert fiber-plastic waste into fuel pellets was proposed to address waste inconsistency and difficulty in pelletization (Kolapkar et al., 2022). The produced pellets are cost-effective, enhanced with high heating value, uniformity, and low environmental impact. The TE analysis and life cycle assessment indicated a pellets' baseline cost of 55.28 dollar per dry tonne. The life cycle assessment results showed that the torrefied product has net-negative GHG emissions, making it an environmentally beneficial feedstock for future processing (Kolapkar et al., 2022)

6.3. Policy support and research and development

Policy support and incentives, in addition to economic and environmental variables, can considerably impact the TE performance of biomass processing methods and how competitive they are compared to other energy technologies (Liu et al., 2022; 2023). Government measures, such as tax breaks, renewable energy objectives, and feed-in tariffs, can help to establish a favorable market environment for biomass energy, making it more appealing to investors (Ma et al., 2021; Farajollahi and Hossainpour, 2023). On the other hand, the absence of supportive policies or the presence of fossil fuel subsidies could discourage the development of biomass energy initiatives and favor other energy options.

The levelized cost of energy (LCOE) is a popular tool for assessing the economic performance of various energy systems (Farajollahi and Hossainpour, 2023). The LCOE considers the overall costs of the facility during its lifetime and derives the average cost per unit of energy produced (Farajollahi and Hossainpour, 2023). It enables a fair comparison of various technologies, considering capital and running expenses. Policymakers and investors can make informed decisions regarding the most economically viable and environmentally friendly energy options by comparing the LCOE of biomass processing methods to that of other sustainable technologies.

Continuous research and development are required to improve the TE performance of biomass processing technologies for bioenergy. Advancements in biomass transformation technologies, such as torrefaction, pyrolysis, densification, gasification, and biorefining, can improve energy conversion efficiency and lower production costs (Cormos, 2023; Makepa et al., 2023). Feedstock collection, logistics, and preliminary processing improvements can enhance the overall economics of biomass energy generation (Makepa et al., 2023). Furthermore, researching synergies between biomass energy and other industries such as agriculture, forestry, and waste management might generate new revenue streams while lowering feedstock prices. For example, using agricultural and organic waste for biomass energy generation can assist in addressing waste management issues while offering a sustainable feedstock supply.

7. Recent research efforts on biomass processing and BSFs production

This section presents recent research efforts on biomass processing and BSF production. The characteristics of biomass feedstock and BSFs are analyzed, focusing on their morphological and microstructural properties. This section is organized into subsections based on the findings and conclusions derived from studies that met the inclusion criteria of the review process.

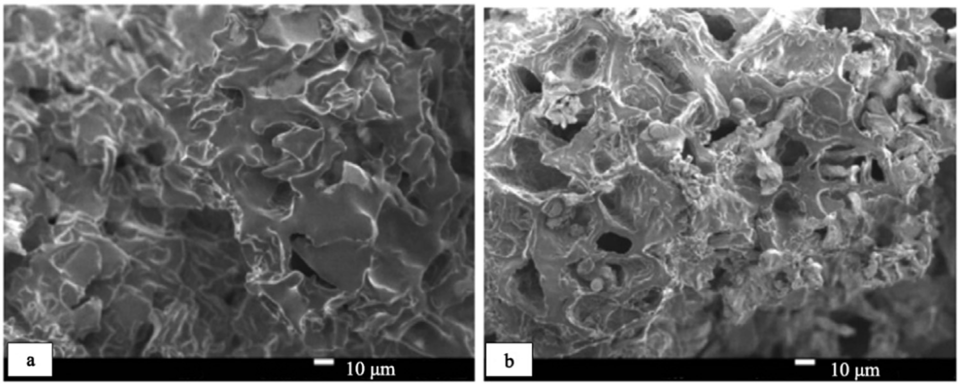

Fig. 7. Scanning electron microscopy (SEM) micrographs of raw spent coffee grounds (a) and spent coffee grounds hydrochar (b) (scale bar is 10 µm; magnification is 500) (Afolabi et al., 2020) with permission.

7.1. Hydrothermal carbonization of biomass feedstock

The hydrothermal carbonization (HTC) method, also known as “wet carbonization” or “hydrothermal treatment”, involves subjectin biomass to high temperatures and pressures in a water-rich environment (Aragón-Briceño et al., 2021). The HTC begins with biomass pre-treatment to modify moisture content and particle size, followed by a hydrothermal reaction in a high-pressure reactor with water to produce a slurry (Román et al., 2020). Under high pressure, the mixture is heated from 180 to 250 °C, resulting in complex physical and chemical processes which break down biomass into carbon-rich particles and produce solid hydrochar (Román et al., 2020). The HTC converts many types of biomass, such as agricultural leftovers, food waste, municipal yard waste, and sewage sludge, into hydrochar or biocarbon, a valuable carbon-rich substance (Román et al., 2020; Sharma and Dubey, 2020; Corton et al., 2021; Le et al., 2022). The hydrochar produced by HTC has excellent uses in renewable energy, as it may be used as a carbon-neutral and sustainable energy source. It is also an effective soil supplement in agricultural applications, boosting soil fertility, water retention, and carbon sequestration (Aragón-Briceño et al., 2021; Ruiz et al., 2023).

Optimizing the HTC process makes it possible to convert biomass into a high-value energy-densified hydrochar (Sharma and Dubey, 2020). Studies have shown that hydrochars produced under different residence times and reaction temperatures exhibit comparable morphological properties, such as pore formation or enlargement (Román et al., 2020; Le et al., 2022). These findings align with the expected devolatilization reactions, fragmentation, and thermolytic decomposition in the HTC process (Afolabi et al., 2020). The HTC conversion of discarded coffee grounds results in hydrochar exhibiting enhanced morphological properties and reduced polycyclic aromatic hydrocarbon concentrations (Afolabi et al., 2020). Fig. 7 depicts SEM micrographs of raw spent coffee grounds and corresponding hydrochar.

Examination of the physical characteristics of olive waste from oil mills after undergoing hydrothermal carbonization revealed that the surface morphology of hydrochars and raw olive pomace exhibited fibrous structures (Erses Yay et al., 2021). The report further showed that the fibrous structure observed in the raw olive pomace was due to the presence of lignin. Though, after hydrothermal carbonization, the surface of the obtained hydrochar exhibited cavities of varying sizes, pores, and shapes. These characteristics were due to the dissolution of organic carbon and degradation brought about by the HTC reactions (Erses Yay et al., 2021).

Optimizing the HTC process is a promising solution for disposing of biomass waste and residues. Using the Arrhenius equation, a study investigated the impact of various HTC severity levels on the fuel properties, storage and transportation, mechanical characteristics, and combustion behavior of hydrochar pellets produced from biomass residue (Sharma and Dubey, 2020). Hydrochar pellets produced from severe HTC had a smoother surface than those from less severe HTC (Sharma and Dubey, 2020; Le et al., 2022). The color of the hydrochar pellets was greatly influenced by temperature, where elevated treatment temperature resulted in darker pellets because of increased restructuring of lignin and carbonization (Sharma and Dubey, 2020). The compression process during pelletization caused the natural binder (lignin) to be extruded and develop a dark and glassy coating, which functions as a solid bridge that enhances the mechanical characteristics of the hydrochar pellets. Research further indicated that the hydrochar pellets produced at higher temperatures had a uniform and smooth surface, while pellets manufactured at lower temperatures had small voids and surface roughness (Cao et al., 2020; Sharma and Dubey, 2020).

Several researchers have proven that the HTC process impacts grindability and particle size distribution (Sharma and Dubey, 2020). Specifically, the HTC conducted at a higher severity factor level significantly enhanced the grindability of feedstock by transforming its lignocellulosic microstructure, leading to a reduced fibrous nature (Sharma and Dubey, 2020). Moreover, the durability of hydrochar pellets can also be significantly influenced by their hydrochar particle size, with finer particle sizes exhibiting better durability properties, which enhances storage properties (Sharma and Dubey, 2020). Fine hydrochar particles with the required moisture content can aid the development of liquid bridges among particles. This encourages attractive molecular forces due to the ability of the particles to create extra surface contact points during densification (Yu et al., 2022b). Conversely, larger hydrochar particles in solid fuels can cause fractures and cracks in the fuels, which impact their durability (Sharma and Dubey, 2020).

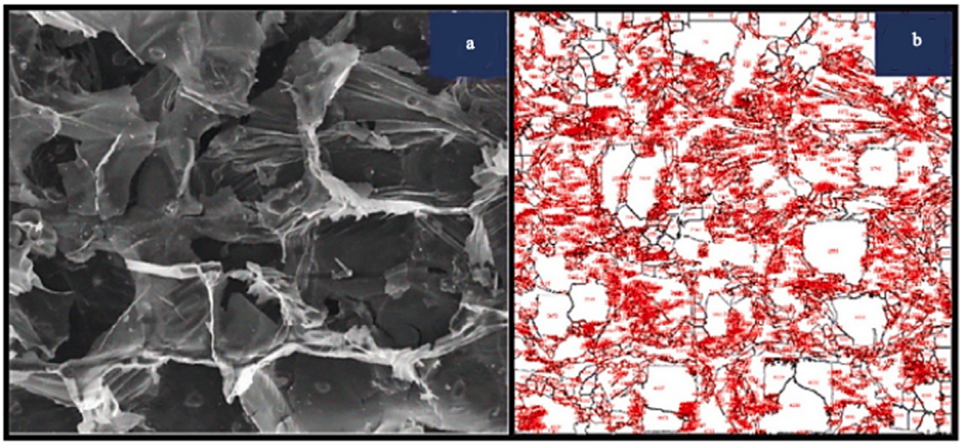

Fig. 8. Banana pseudo-stem biochar produced through slow pyrolysis: (a) surface morphology and (b) ImageJ analysis of the number of pores (Abdullah et al., 2023).

Setter et al. (2020) have suggested that lower treatment temperatures can prevent the formation of defects and cracks in char solid fuels, which are frequently caused by high heating rates. When the treatment temperature is high, larger internal cavities and more open char structures are created due to the fast liberation of volatile compounds, leading to an increased internal pressure and coalescence of smaller pores. This phenomenon increases the surface area and pore volume of the char (Salimbeni et al., 2022; Yu et al., 2022b). The study also revealed that the density and durability of pellets exhibited a notable increase following HTC treatments. This indicates that as the treatment temperature increased, the particles in the treated samples became more compactly fused (Yu et al., 2022b).

7.2. Biomass pyrolysis

Several researchers have reported how the pyrolysis process influenced the morphological properties of BSFs (Abdullah et al., 2023; Mu et al., 2023). A study was carried out to assess the characteristics of biochar manufactured from banana pseudo-stem through fast and slow pyrolysis processes (Abdullah et al., 2023). The results showed that the biochar produced *via* slow and fast pyrolysis varied significantly regarding pore quantity and surface morphology. Analysis of the field emission scanning electron microscopy (FESEM) results revealed that the biochar obtained from fast pyrolysis had lower porosity and surface area. This observation is associated with the quick depolymerization caused by the higher heating rates adopted during pyrolysis (del Pozo et al., 2021). Conversely, the biochar obtained *via* slow pyrolysis displayed better morphological properties, suggesting its possibility for use as a solid biofuel (Varma et al., 2019).

Fig. 8 shows the transverse section of the feedstock biochar with the magnification of 1000, while the structure of banana pseudo-stem biochar made through fast pyrolysis was shown in Fig. 9. The biochar produced through slow pyrolysis of biomass displays

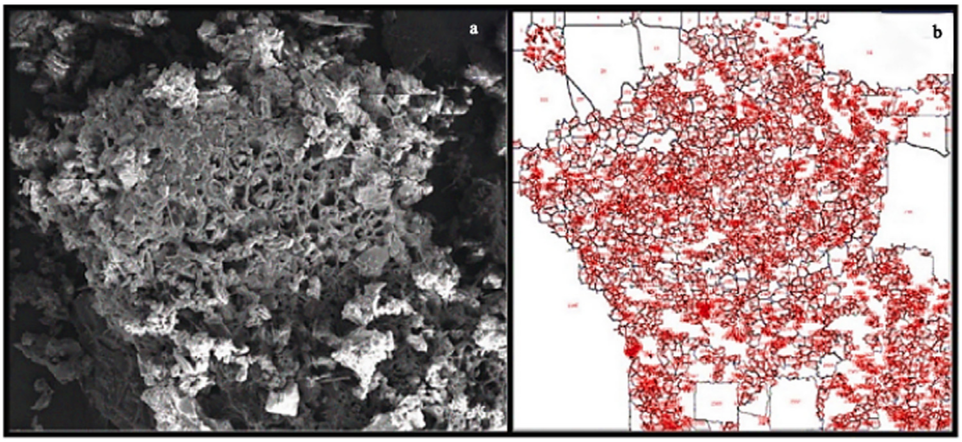

Fig. 9. Banana pseudo-stem biochar produced through fast pyrolysis: (a) field emission scanning electron microscopy (FESEM) and (b) ImageJ analysis of the number of pores (Abdullah et al., 2023).

an irregular pore and cellular structure, and these characteristics are visible on the biomass surface. In contrast, the fast pyrolysis biomass char has a rough surface and a well-defined structure (Abdullah et al., 2023).

Previous works have indicated that the properties of BSFs are influenced by the type of biomass used (Yu et al., 2022b; Mu et al., 2023). The biochar produced from corn stover feedstock through microwave-assisted pyrolysis exhibited remarkably pure pores with very few carbon impurities and a higher pores surface area (Fodah et al., 2021). By incorporating adsorbents into the pyrolysis process, the absorption of microwave energy was improved, facilitating the decomposition of remaining volatile components within the biochar. This process generated new pores and resulted in higher production of biochar with greater pore volumes and reduced levels of carbon impurities (Fodah et al., 2021). The addition of adsorbents showed a significant improvement in pore volume, surface area, micropore area, and pore diameter due to the higher process temperatures. Further, adding adsorbents gave biochar a high calorific value, and the emission of harmful gases, such as sulfur, was reported to reduce (Fodah et al., 2021).

An investigation of the number of pores in biochar using ImageJ software (Fig. 9a and b) revealed that biomass char derived from fast pyrolysis has lower pores compared to char derived through a slow pyrolysis process. The difference in the number of biochar pores produced through fast and slow pyrolysis is connected to the treatment heating rate. Smaller pores were created by fast pyrolysis than by slow pyrolysis (Fodah et al., 2021). Another study reported that char pore volumes and surface area increase with pyrolysis temperature (Maaoui et al., 2023). The report further showed that the augmentation in surface area and micropore volume was attributed to the enhanced decomposition of lignin and the swift liberation of volatile matter. These processes contribute to the formation of a more sophisticated structure.

The morphological analysis of pellets produced from low-temperature pyrolysis of coffee residues was assessed to determine its potential for solid fuel applications. A stereoscopic picture of the pellets revealed that the pellets had rough surfaces with cracks. This indicated weak bonding between particles during compaction (Setter et al., 2020). Further analysis showed that adding water to feedstock before pellet production impacted the process. However, the temperature, particle size, feedstock type, and compaction pressure were critical factors that influenced the morphological and strength properties of the resulting pellets (Setter et al., 2020; Ali et al., 2022; Chen et al., 2022).

The production of biomass pellets subjected to heat treatment using pine wood and pyrolysis oil as binders were studied (Riva et al., 2019a). Using pyrolysis oil as a binder gave the pellet good strength properties. The SEM analysis of the biocarbon pellets showed that pyrolysis oil particles acted as a binding agent among bigger biochar areas. The heat-treated pellets have a homogenous and compact structure with enhanced mechanical properties because of the carbonization of pyrolysis oil particles, improving the strength characteristics of the char structure. SEM results also showed that the pellets had bounded particles with unique partially porous structures (Riva et al., 2019a).

A separate study examined pellets produced from cotton stalks *via* thermal treatment at temperatures ranging from 180 to 280 °C and a residence time of 120 min (Cao et al., 2020). The skeleton structure of crystalline cellulose was reported as the main factor affecting the strength of the biochar solid fuel. At the same time, lignin played an influential role in forming solid bridges and improving bonding performance. Nevertheless, subjecting biochar pellets to heat treatment at 280 °C resulted in a total transformation of crystalline cellulose into amorphous carbon and decreasing compressive strength (Cao et al., 2020). The high carbonization temperature of lignin also led to a loss in its bonding capacity, further contributing to the decline in compressive strength (Ali et al., 2022).

The characteristics of biochar can vary greatly, subject to the conditions of the process methods and the type of feedstock used (Abdullah et al., 2023). del Pozo et al. (2021) opined that surface areas of biochars characteristically increase with higher treatment temperatures and are also influenced by the percentage of lignin content in the feedstock. The biochars produced at low-temperature pyrolysis have shallow surface areas because of low lignin content and lack of activation treatment. Also, inorganic compounds from tars, ash, and other decomposition materials could plug the pores of biochars, which could be preferential due to the long residence time at low treatment temperatures (del Pozo et al., 2021).

7.3. *Utilization of additive and binder in BSFs production*

Numerous studies have demonstrated that the durability and strength of BSFs produced *via* thermally treated biomass are lower than those produced from non-thermal treated biomass (Zhang et al., 2020b; Manouchehrinejad et al., 2021; Guo et al., 2022a; San Miguel et al., 2022). This difference in durability can be connected to changes in the microstructure of biomass that occur during the thermal treatment process (Yang et al., 2019; Sharma and Dubey, 2020). Also, thermal treatment often results in voids and gaps between particles, which leads to a less durable and more fragile structure of thermally treated biomass particles (Yang et al., 2019). A comparison between the surfaces of non-treated and treated corn stover particles and pellets is presented in Fig. 10. The glassy surface and smoothness of a non-treated particle are shown in Fig. 10a, while Fig. 10b shows the surface of a treated particle. The non-treated particle appears to have a solid bridge without visible cracks at this scale, enhancing binding affinity.

The microscopic image of the surface of the treated and non-treated biomass is shown in Fig. 10c and 10d, respectively. The surface of the thermally treated pellets shows evident biomass particle interlocking and melting, which could lead to stronger particle-particle bonding (Yang et al., 2019). This is because a portion of hemicellulose is removed during thermal treatment, and specific cell walls are destroyed, resulting in inter-particle voids and gaps in the treated biomass (Dai et al., 2019; Manouchehrinejad et al., 2021). Further analysis of the microscopic image revealed that removing hydroxyl groups from lignin during thermal treatment increased the non-polar C–C bonds, making treated particles harder to bind for the production of solid fuel. Consequently, lignin cannot perform its natural binding function, leading to difficulty in performing densification on treated biomass particles compared to non-treated ones (Yang et al., 2019).

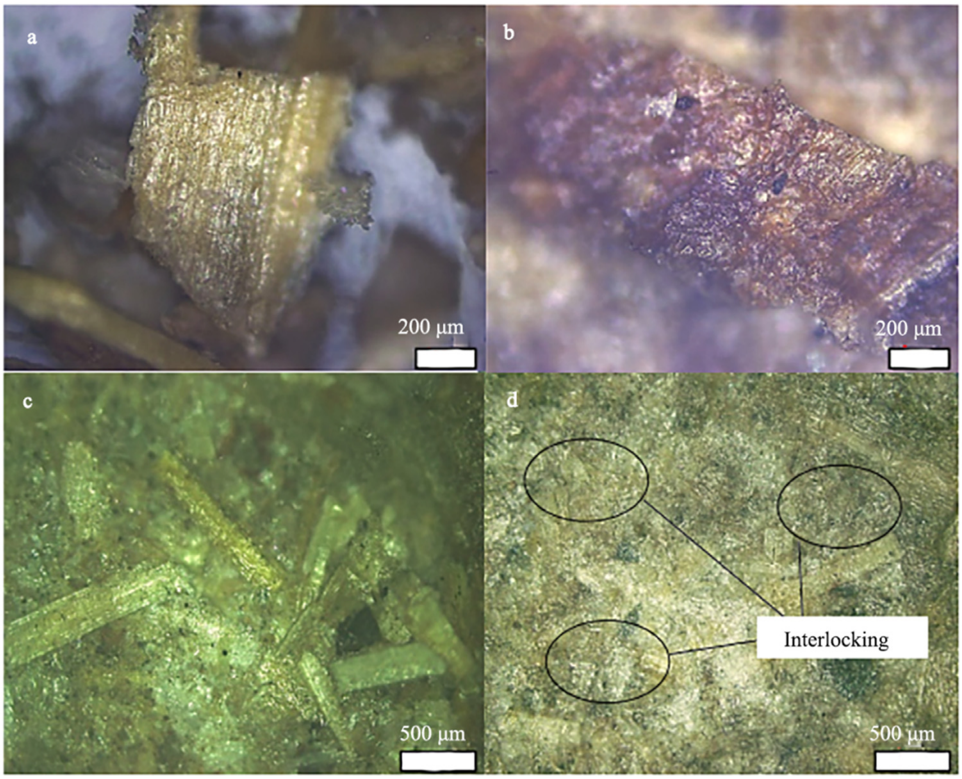

Fig. 10. Surface comparison of non-treated and treated corn stover particles and pellets: (a) non-treated corn stover particles, (b) treated corn stover particles, (c) non-treated pellet, and (d) treated pellet (Yang et al., 2019) with permission.

A study conducted on three agricultural residues (sugar cane bagasse, rice rusk, and coffee husk) focusing on investigating the influence of the lubricity of the binder on pellet morphology revealed that the utilization of a binder additive did not affect the morphology of pellets made from sugar cane bagasse and rice husk (Marrugo et al., 2019). However, adding a binding agent impacts the coffee husk pellets, making the pellet more malleable and softer.

The utilization of cassava starch and calcium carbonate as additives in solid fuel production has been investigated at different proportions (Matkowski et al., 2020). The variation of the percentage of calcium carbonate and cassava starch led to a reduced geometric mean and a more even particle size distribution at 6 % binder addition compared to pure feedstock. This resulted in a superior densification additives efficiency, which was qualified by a consistent particle size distribution (Matkowski et al., 2020).

The heat treatment of charcoal composite pellets produced using bio-oil as a binder can reduce pellet porosity due to the depolymerization of binder in the macropores (Riva et al., 2019a). A study reported that bio-oil binders improve pellet storage and transportation property and minimize charcoal pellet production costs (Surup et al., 2020).

An investigation of the impact of process parameters on particle binding during biomass pelleting revealed that the hammermill grind size and moisture content of feedstock significantly impacted the produced pellet properties (Tumuluru et al., 2020). The pelletizing process parameters, such as residence time, moisture content, and hammermill screen size, influence the geometric mean of the feedstock length and diameter of the pellet particle. The X-ray computed tomography scan analysis revealed the presence of voids, which could be caused by weak adhesion between the particles (Tumuluru et al., 2020). For most types of biomass, a dosage of 1%–2% (*w*) halloysite additives is sufficient to reduce ash-related issues, such as fouling, slagging, and chloride corrosion in biomass-fired boilers (Sobieraj et al., 2021).

7.4. Biomass reactivity process

The suitability of olive stones biomass as a low-moisture and high-density feedstock for energy applications was investigated through a torrefaction process (Trubetskaya et al., 2020). The report showed that the ash composition and lignocellulosic content of the biomass influence the reactivity process of biomass during torrefaction. A particle size, temperature, and residence time of 2 mm, 270 °C, and 30 min, respectively, were suggested as the most suitable parameters for optimum reactivity process and densification in pilot plant operations (Trubetskaya et al., 2020).

Analysis of the physical and chemical properties of biochar produced from the gasification of walnut shells and distillation sludge char revealed that higher gasification reactivity of biochar was associated with its abundant porous structures and amorphous carbon content (Khiari et al., 2019; Diao et al., 2022). In contrast, the distillation sludge char produced at an elevated temperature (1100 °C) displayed a regular and smooth surface with graphite structures, making it problematic to offer active carbon sites for reaction with gasifying agents (Diao et al., 2022). According to Chun and Simson (2022), the biochars produced through CO_2 co-pyrolysis exhibited similar reactivity for CO_2 gasification, despite some having higher moisture capacities, which may be related to their surface area. The study also emphasized the significance of ash content and the choice of feedstock in determining the reactivity of biochar for gasification purposes.

In another study, the effect of wood pellets on the reactivity of coke with CO_2 was investigated with particular attention to how the microstructure properties of the coke were affected (Kieush et al., 2022). It was opined that adding biomass pellets does not have a meaningful impact on the microstructure characteristics of coke. This suggests no chemical interaction exists between the biomass pellet and the coke. However, adding biomass pellets increases the reactivity of the coke, which was linked to the isotropic feature of the biomass pellets (Kieush et al., 2022). The char produced from biomass pellets affected the internal structure of the coke, a change in the microstructure at the boundary surface with char generated from the biomass pellet. However, the structure of the coke outside the boundary surface is similar to conventional coke. Further analysis showed that the isotropic texture of the biochar also increased reactivity, more significant than the highly ordered carbon structure found in conventional coke when reacting with CO_2 (Kieush et al., 2022).

Researchers are drawn to biochar because of its valuable properties and potential for carbon sink (sequestration) and reactivity (Riva et al., 2019a; Koskela et al., 2023). A study thoroughly explains the modifications in the chemical makeup and structure of lignocellulosic biomass during the carbonization process, and the source of reactivity in the resulting biochar is found in Qin et al. (2022). The increased porous characteristics of biochar could also assist air access and distribution, leading to enhanced thermal reactivity during combustion. Therefore, densification before heat treatment minimizes reactivity because it reduces porosity and enhances mechanical strength. Densification and treatment temperature influence the characteristics of biochar produced during thermal treatment, while particle size influences the biochar yield (Koskela et al., 2023).

7.5. The BFS property: catalyst-based biochar, thermal treatment, and deep eutectic solvent technique

Biochar is a stable and carbon-rich type of charcoal. It is produced *via* the biomass thermochemical conversion process, which involves heating biomass in an inert or low-oxygen atmosphere (Abdullah et al., 2023). Biochar is a sustainable method for managing organic waste, transforming it into a valuable resource instead of contributing to pollution. The renewable energy co-product generated during biochar production adds to its ecological sustainability by supplying bioenergy for heat and power generation. Soil amendment is another biochar application (Qin et al., 2022). Biochar improves soil fertility, water retention, and accessibility to nutrients when mixed into the soil. Furthermore, biochar is essential for carbon sequestration (Dumortier et al., 2020). Biochar combats climate change by lowering the release of GHG and its environmental impact by sequestering CO_2 from the atmosphere and conserving it in soil for an extended period.

The particle size of the biomass feedstock utilized for making biochar can substantially impact biochar yield. Smaller particle sizes generally produce larger biochar yields (Abdullah et al., 2023). The larger surface area of finely ground biomass provides improved heat transfer and reactivity during thermochemical transformation. This improves biomass carbonization, transforming more feedstock into biochar than other byproducts (Li et al., 2019). Consequently, the biochar yield increases as the particle size of the biomass feedstock decreases. Larger particle sizes, on the other hand, may contain spaces of trapped air, restricting contact between the biomass and the heat source and impeding the thermochemical transformation process. This can result in insufficient carbonization and decreased biochar production (Abdullah et al., 2023).

Catalyst-based biochar is gaining popularity due to its favorable characteristics like porosity, surface area, and functionality. These characteristics are determined by various factors, including biomass source and processing methods, such as thermal treatment (Gaurav et al., 2020). These key parameters must be optimized to enhance catalytic characteristics. Non-thermally treated feedstock has a low percentage of pore area, but porosity increases with the thermal treatment level, resulting in a higher percentage of pore area (Yu et al., 2022b). The thermal treatment level strongly correlates with compressive strength and pore area percentage of BSFs (Li et al., 2019; Koskela et al., 2023).

During thermal treatment, heat is transferred within a biomass feedstock by two methods: convection and conduction (Gupta et al., 2021). Heat transfer through the BSFs contact surfaces by conduction, while convection occurs when volatiles are liberated from the BSFs and transfer heat as they move through the surrounding gas or air. The porosity of the biomass feedstock and BSFs increases as volatiles are released, resulting in better heat transfer through the convection method (Gupta et al., 2021). Surup et al. (2020) discussed how the properties of charcoal BSFs could be influenced by particle heat exchange: permeability between hot gases and the BSFs or feedstock results in more stable heat transfer.

Research has shown that high porosity indices of biomass feedstock enhance the thermal transformation process as porous structures permit less complex reactions (Gonçalves et al., 2021). Shangdiar et al. (2021) present an environmental scanning electron microscopy (ESEM) photo of a coconut shell and rice straw after thermal processing at 300 °C. The ESEM photo showed that the surface structure of the feedstock changes from clear to dense and loose. The holes in the cell wall of biomass feedstock become enlarged and more evident after the thermal process. This is because of the liberation of volatile substances, resulting in a porous and fine structure of the biochar. The report also showed that biochar’s surface area and yield increase with treatment temperature up to 300 °C, beyond which the yield decreases, and chemical functional groups and surface area of biochar decrease as well (Shangdiar et al., 2021).

A deep eutectic solvent (DES) is a solvent generated by combining more than one solid or liquid substance to form a eutectic mixture (Guo et al., 2022b). Eutectic mixtures are a type of mixture in which the melting point is much lower than the melting temperatures of its constituents (Prabhune and Dey, 2023). This liquid state remains ambient or somewhat higher, making deep eutectic solvents a versatile and flexible alternative to standard organic solvents.

Due to their low toxicity and biodegradable properties, DES has gained popularity in various scientific and industrial uses. It has been investigated as a prospective substitute for traditional volatile organic solvents in chemical reactions, extraction procedures, and as electrolytes in energy storage devices, among other things (Saravanan et al., 2023a). Furthermore, the capacity to develop and control the properties of deep eutectic solvents through various component combinations makes them an intriguing and attractive area for study in sustainable technology (Cai et al., 2019).

A DES technique has been developed to enhance the structural integrity and durability of energy pellets made from residual wheat straw. This method is environmentally friendly since the solvent can be reused (Guo et al., 2022b). The proposed method of using a DES for pellet production involves partially swelling and dissolving the biomass, resulting in better lignin access. This enables the lignin to redistribute and reform at interfaces, leading to more effective binding and enhanced pellet durability. This method significantly improved pellet durability, with an increase of 90%–97% compared to pellets made from untreated biomass. Moreover, molecular simulations recommend that the residual lignin that remains after the treatment process function as a binding agent and strengthens the non-bonded interface with cellulose, improving the strength of the solid fuel (Guo et al., 2022b).

8. Conclusions

The review comprehensively discusses research on BSFs, including biomass sources, processing methods, and morphological and microstructural properties. The review process involved a broad search strategy to identify relevant studies.

Biomass sources for energy production were explored. Wood, wood residues, forest residues, municipal solid wastes, agro-residues, energy crops, and livestock wastes account for 67%, 5%, 1%, 3%, 4%, 3%, and 3% of biomass sources used in bioenergy generation, respectively. The various biomass sources have distinct advantages and disadvantages. Forest wastes are abundant, but the collection is expensive. Agricultural residues are reliable, but their characteristics depend on farm location, soil composition, crop type, and weather conditions. Food waste is abundant in cities, but it must be adequately managed. Municipal solid waste reduces landfill, however, requires extensive sorting. Some of the drawbacks of energy crops are competition for land utilization, high costs, and labor requirements. Livestock waste reduces methane emissions, but large amounts of food waste can pollute the environment. Wood and wood residues are wide availability, with a lower carbon footprint than other biomass and conventional energy sources. However, if wood and wood residues are not burned in a modern boiler and stoves, they can produce hazardous substances, such as particulate matter, carbon monoxide, nitrogen oxides, and so on. The best biomass source is determined by regional variables, sustainability, and energy requirements.

Various thermal treatment technologies were discussed for converting biomass and residues into usable energy, including gasification, torrefaction, carbonization, HTC, and pyrolysis, each with advantages and disadvantages regarding energy performance, techno-economic considerations, and environmental impact. Gasification stood out as a highly efficient process for producing syngas from different biomass sources, although it requires a substantial capital investment. Pyrolysis efficiently transforms biomass into bio-oil, char, and gases, with economic feasibility determined by feedstock availability. Carbonization generates biochar at a low cost and has the potential to sequester carbon in the soil. Torrefaction increases the energy density of biomass, making it acceptable for co-firing with coal. Hydrothermal carbonization (HTC) efficiently processes wet biomass and organic waste while requiring less energy.

Different densification techniques were described, with mechanical stamping press, extrusion, and roll press suitable for large-scale production, while piston press and hydraulic press more ideal for small-scale production. Thermal treatment of biomass often leads to lower durability and strength of pellets than non-thermally treated biomass. Voids and gaps between particles result in a more fragile structure due to the removal of hemicellulose and the destruction of cell walls. Heat-treated biochar pellets have a compact structure with enhanced mechanical properties. Crystalline cellulose and lignin significantly determine the strength and bonding performance of biochar pellets.

Innovative approaches like using a deep eutectic solvent for pellet production improved pellet durability by enhancing lignin access and binding. These findings provide insights for optimizing and designing solid fuels for energy applications, enhancing properties like durability, strength, and thermal reactivity.

Understanding the morphology characteristics of BSFs allows energy specialists to optimize and design solid fuels for energy applications. The mechanical properties such as ductility, strength, durability, impact resistance, and drop to fracture heavily rely on the microstructural properties of the solid fuel.

The morphological properties of hydrochars obtained through HTC are influenced by residence time and reaction temperature. The fibrous structure of raw biomass is transformed into cavities, pores, and shapes after HTC due to the dissolution of organic carbon and degradation. The surface smoothness and color of hydrochar pellets are affected by HTC conditions, with higher temperatures resulting in darker and smoother pellets. The HTC process also impacts the grindability, particle size distribution, density, and durability of the pellets. Biochar produced *via* slow and fast pyrolysis exhibits variations in pore quantity and surface morphology. Fast pyrolysis produces biochar with lower porosity and surface area, while slow pyrolysis yields biochar with better morphological properties suitable for solid biofuel. Analytical approaches, such as spectroscopy, microscopy, scattering, and diffraction, are used to study the morphological and microstructural properties of BSFs, enabling researchers to analyze and visualize the structure at different scale levels.

9. Recommendations for future research

Based on the analysis and conclusions presented, here are some recommendations for future research in the field:

(1) More comprehensive studies are needed to focus on the evolution from biomass to hydrochar, as most existing research has primarily focused on the final hydrochar products rather than the intermediate stages. Understanding this evolutionary pathway is crucial for enhancing the hydrothermal process and adjusting the properties of the resulting products. Furthermore, it is essential to establish the relationships among different structures within lignocellulosic biomass through various calculations and observations. By considering partial and holistic perspectives, researchers can gain a deeper understanding of the basic structures in lignocellulosic biomass and their impact on the overall process. Additionally, investigations of the comprehensive representation of the internal structure of lignocellulosic biomass under different conversion conditions are needed to overcome the limitations of previous studies.

(2) Char recovery from different biomass sources has demonstrated a net energy balance and potential economic viability. However, comprehensive experimental runs and characterizations of char under optimized conditions are required to ensure consistent and reliable char products from different biomass sources and processing methods. Furthermore, a thorough techno-economic analysis of the biomass processing methods for recovering bioenergy from various biomass sources is necessary to determine its scalability and economic viability. Additionally, the performance and emission levels of char, particularly in stand-alone combustion or co-combustion scenarios, need to be investigated further, along with practical applications for renewable fuel.

(3) Further investigation is necessary to comprehend the impact of thermal treatment on the durability and strength of biomass pellets. This can involve studying the mechanisms underlying the formation of voids and gaps in thermally treated biomass particles and exploring methods to enhance the structural integrity of such pellets.

(4) Given the importance of additives and binders concerning the morphological and microstructural aspects of BSFs, it is crucial to develop a numerical model to predict the appropriate dosage of densification additives and binders for different biomass feedstock. This model can be a valuable tool for optimizing biomass fuel production processes. The reliability of research outcomes will be enhanced through these measures. It will result in cost and energy savings in power plant design while also facilitating comparative analysis of various biomasses processing methods using a single type of biomass. This approach will contribute to a deeper understanding of biomass processing methods for sustainable energy generation.

(5) Future research can prioritize the examination of how various residence times, reaction temperatures, and biomass sources affect the morphological properties of BSFs from hydrochars, aiming to gain deeper insights into the HTC process and enhance the production of hydrochars solid fuels for energy applications. Additionally, it is recommended to determine the most suitable pyrolysis method for producing biochar with desired morphological characteristics for solid biofuel applications, offering the potential for future studies. Also, investigating char morphology and temperature changes during gasification is necessary to enhance the understanding of the gasification process.

(6) Future research can explore alternative methods for pellet production to improve the morphological properties and durability of biomass pellets, such as utilizing deep eutectic solvents. This exploration can involve investigating the effects of deep eutectic solvents on biomass swelling, lignin redistribution, and binding properties of the resulting pellets.

(7) Further research into the environmental impacts and sustainability of BSFs is recommended, especially life cycle evaluation, emissions, waste collection and disposal, land and water management, and social-economic implications. This will promote environmentally sustainable biomass-based energy alternatives and help people make well-informed decisions.

By addressing these research recommendations, energy professionals can further advance the understanding of the morphological properties of BSFs and develop more efficient and sustainable energy production processes.

Declaration of Competing Interest

The authors have no financial or non-financial interest to disclose.

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