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Review article

Investigation of the potential biomass waste source for biocoke production in Indonesia: A review

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ABSTRACT

Using biomass waste for renewable energy and sustainable fuel production has gained significant attention recently. This review investigates the potential biomass waste sources for biocoke production in Indonesia. Biocoke, a form of solid fuel derived from biomass, has emerged as a viable alternative to traditional coke in various industrial applications, including steelmaking. This review comprehensively analysed available literature and data sources to identify Indonesia's most abundant and suitable biomass waste sources. The assessment considered biomass availability, sustainability, energy content, and compatibility with biocoke production processes. The environmental impacts associated with the production and utilization of biocoke were also considered. The findings reveal that Indonesia possesses a rich diversity of biomass waste sources with a high potential for biocoke production. Agricultural residues, such as rice straw, corn stalks, and palm oil residues, are identified as promising feedstocks due to their abundance and availability throughout the country. Moreover, biomass waste can contribute to waste management and alleviate environmental concerns associated with open burning and landfilling. The review also highlights the importance of sustainable practices in biomass waste collection and processing. Efficient collection and logistics systems and advanced biomass conversion technologies are crucial to ensure biocoke production's economic viability and environmental sustainability. Furthermore, the economic viability of biocoke production is examined by considering factors such as feedstock costs, energy efficiency, and market demand. The potential challenges and barriers, including technological, regulatory, and market-related aspects, are also discussed to provide a comprehensive overview of the feasibility of large-scale biocoke production in Indonesia. Overall, this review underscores the significant potential of biomass waste as a valuable resource for biocoke production in Indonesia. By harnessing the abundant biomass waste streams available in the country, Indonesia can reduce dependence on fossil fuels, mitigate greenhouse gas emissions, and promote sustainable development in the energy sector.

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1. Introduction

The depletion of fossil fuels, national energy security, climate change, uncertain energy prices, and the energy carbon footprint of the industry has become comprehensive issues. Hence, attention to finding alternative energy becomes a must. Efforts to utilize and synthesize renewable energy sources have been reported from several developing countries and small islands worldwide (Dai et al., 2016; Debanjan and Karuna, 2022; Erdiwansyah et al., 2020,?; Hua et al., 2016; Liu, 2019; Renn and Marshall, 2016; Tripathi et al., 2016; Zamfir et al., 2016; Zhao et al., 2022). Developments with expertise carried out by several countries are very progressive, especially for solar and wind energy generation (Devine-Wright, 2005; Esmaeilion et al., 2022; Patel and Beik, 2021). Meanwhile, using existing technologies, biomass raw materials from renewable energy sources can be converted into renewable energy generators (Basu, 2018; Chartier et al., 2013; Chartier and Palz, 2012; Grassi et al., 2003). The footprint of carbon emissions originating from industries such as steelmaking has raised concerns, especially regarding the innovation of fuels based on reducing agents and biomass (Shahbaz et al., 2020; Suopajärvi et al., 2013). The metallurgical industry, with a steel production level of 7.5 million tons in Malaysia, is an example that can be given (Abd Rashid et al., 2014). The industry generally generates the trend of increasing carbon dioxide emissions, as shown in Fig. 1 (Liu et al., 2019; Mustapa and Bekhet, 2016; Shahid et al., 2014).

The properties of biochar, syngas, composition, bio-oil and liquid phase can be predicted through machine learning (ML) (Li et al., 2023; Mishra and Mohanty, 2022). Energy production, such as biofuels from municipal waste using pyrolysis technology, has been discussed in research (Mahari et al., 2021). This research examines explicitly the pyrolysis technique to convert municipal waste into energy that has high value. Karakterisasi produk pirolisis lumpur melalui teknologi pembelajaran mesin sehingga menjadi produk berharga baru-baru ini telah dibahas (Shahbeik et al., 2022). Pyrolysis, on the other hand, is typically performed at temperatures that are lower than those of incineration and gasification. As a result, high-boiling-point heavy metals like lead, nickel, copper, zinc, and iron found in sludge do not volatilize during the pyrolysis process. Instead, these metals concentrate in the carbonaceous solid matrix (Barry et al., 2019; Udayanga et al., 2019). Producing bioenergy carriers that are based on biomass rather than first-generation bioenergy is also highly advantageous given the current issues encountered in the world, particularly the Ukraine-Russia war and its unfavourable impacts on the fuel and energy supply chain, as described in a recent paper, which was published in a scientific journal (Esfandabadi et al., 2022).

The improvement of biocoke fuel used for metallurgical and steel-making processes has been widely reported in the literature. However, its utilization and application have not been fully implemented in practice (How et al., 2019; Mansor et al., 2018). Thus, the application level will likely partially substitute top Coke with biocoke. In addition, biocoke is also used as an injection to replace partially pulverized coal (Mellin et al., 2014; Wei et al., 2013). The extensive use of biocoke and its synthesis in the metallurgical industry has been investigated by (Mellin et al., 2014; Suopajärvi, 2014).

The briquette fuel that has been widely produced so far is almost like biocoke. However, briquettes are generally produced by torrefaction, which involves heating biomass without oxygen. Meanwhile, biocoke production does not go through torrefaction; for example, biocoke production in Japan only requires the highest heating of 200 °C. Biocoke without torrefaction can produce higher energy than briquette production using torrefaction. This thermal treatment removes moisture and volatile compounds, creating solid, energy-dense material. The resulting biocoke has properties like traditional fossil-based coke, making it suitable for applications in industries like steelmaking and as a reducing agent in various chemical processes. Advantages of biocoke include its renewable nature, reduced carbon footprint compared

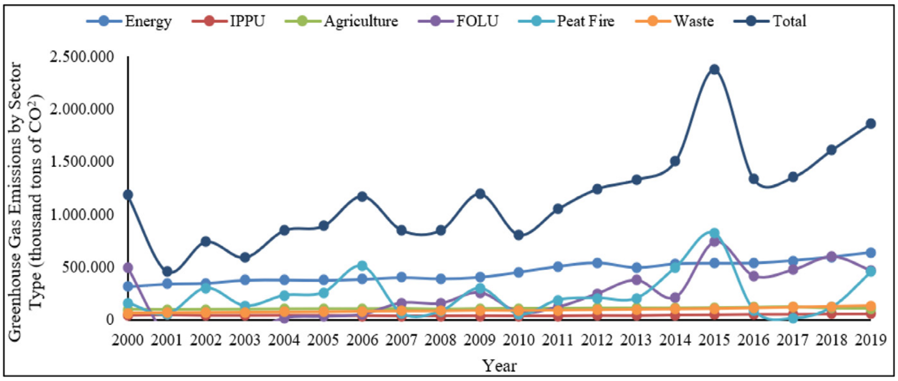

Fig. 1. Trends in carbon dioxide emissions from various sectors in Indonesia Period 2000–2019 (BPS, 2022).

to fossil fuels, and potential for waste utilization. It can be produced from various biomass feedstocks, including agricultural residues, wood waste, and energy crops, providing opportunities for biomass valorization and waste management. However, it is essential to consider specific challenges associated with biocoke production and utilization. These include the high energy input required for the torrefaction process, the need for large-scale biomass supply chains, and the potential impact on land use and food security if energy crops are extensively cultivated. Additionally, biocoke's market competitiveness and economic viability are crucial compared to fossil-based alternatives.

Indonesia is known for its abundant biomass resources, which can potentially be utilized to produce biocoke fuel. The country possesses a diverse range of biomass waste, including agricultural residues, forest residues, palm oil waste, and municipal solid waste. These biomass resources can serve as valuable feedstocks for biocoke production. Agricultural residues such as rice straw, corn stover, sugarcane bagasse, and oil palm are generated in significant quantities in Indonesia. These residues can be collected and processed for torrefaction to produce biocoke. Forest residues, such as wood chips and sawdust, are also available due to the country's extensive forestry industry. Palm oil waste, including empty fruit bunches, palm kernel shells, and fibre, is another abundant biomass resource in Indonesia. The palm oil industry generates substantial amounts of these residues, which can be utilized for biocoke production or other biomass conversion processes. In addition to agricultural and forestry waste, Indonesia has a substantial amount of municipal solid waste (MSW). MSW, including organic waste, can be processed through advanced techniques such as anaerobic digestion or gasification to produce biogas, which can be further upgraded to biocoke. However, it is important to note that while biomass resources are available in Indonesia, their efficient and sustainable utilization for biocoke production requires the appropriate collection, logistics, and processing infrastructure. Additionally, consideration must be given to environmental and social factors to ensure the sustainable sourcing of biomass feedstocks without negatively impacting food security, land use, or ecosystems.

This literature review aims to identify and discuss the recent advancements and novel approaches in producing biocoke from biomass waste in Indonesia. As a country rich in biomass resources, Indonesia holds significant potential for utilizing agricultural residues, forest residues, palm oil waste, and municipal solid waste for biocoke production. By examining the current state of research and industrial practices, this review sheds light on innovative methods, technological developments, and sustainability considerations in the Indonesian context. The findings contribute to understanding the opportunities and challenges associated with biocoke production and provide valuable insights for further research and development. This literature review comprehensively analyses the biocoke production from biomass waste in Indonesia. Besides that, it is a valuable resource for researchers, policymakers, and industry stakeholders interested in sustainable biomass utilization for energy purposes in Indonesia.

2. Biocoke raw material

Biocoke solid fuel is a sustainable biomass derivative having low sulfur properties, affordable availability and an economically efficient production process system (Huang et al., 2016a,b). Biocoke, also known as biomass coke or green coke, is a type of solid fuel derived from renewable biomass sources. It is commonly used as a substitute for traditional petroleum-based coke in various industrial processes, particularly in the steel and iron industries. Thus, the relationship between characteristics and rules for biocoke production with biomass pyrolysis is irreversible so that organic matter can undergo thermochemical decomposition at high temperatures and without oxygen (Sanna et al., 2009). Biocoke can also be re-upgraded with pyrolysis oil using rapeseed meal and wheat germ biomass using Thermo-T or similar vis-breaking technology (Sanna et al., 2009). The raw materials used in the production of biocoke can vary depending on the specific process and technology employed. However, typical biomass feedstocks such as wood chips, sawdust, or wood pellets are used for biocoke production. Crop residues and byproducts from agricultural activities can serve as raw materials. These include straw, rice husks, corn stalks, and sugarcane bagasse. Biomass can also be utilized in forest management activities, such as logging residues, tree bark, and branches. In addition, several organic waste materials, such as peanut shells, coconut shells, and olive pits, can be used as raw materials for biocoke production. The biomass feedstock is typically subjected to a thermal treatment process called pyrolysis, where it is heated without oxygen to produce biocoke. The resulting biocoke can then be used as a fuel or reducing agent in industrial applications.

Furthermore, because some or all of the biocoke is sourced from photosynthetic plant material, the low sulfur content has implied low pollutant emissions (Florentino-Madiedo et al., 2017; Montiano et al., 2013). To mitigate greenhouse gas (GHG) emissions, biocoke fuel is highly efficient and allows for carbon-neutral combustion (Information, 2015). In addition, biocoke can also inhibit the decomposition of biomass in landfills (Fuchigami et al., 2016). Biocoke production has a low price of about 31% compared to synthetic biomass briquettes. However, the selling price of the product is still higher than that of briquettes (Fuchigami et al., 2016). Biomass briquettes can increase the high bulk density of biocoke because the compounds produced allow for good handling, storage, and fuel transportation at the lowest cost (Montiano et al., 2014).

Classification of biocoke as a fuel because it is produced from solid raw material sources that are compatible with the use of fuels and are supplied for power generation and thermal energy (El-Tawil et al., 2021). The biomass and pure coal systems are two distinct approaches to energy generation that involve the combustion of different fuel types (El-Tawil et al., 2021). Biomass refers to organic materials derived from plants and animals, such as wood chips, agricultural residues, dedicated energy crops, or organic waste. These materials are renewable resources, as they can be continuously replenished. Coal is a fossil fuel formed from the remains of plants that lived and died millions of years ago. It is a non-renewable resource that takes millions of years to start and cannot be replenished on a human timescale. Biomass systems can achieve relatively high energy conversion efficiency, especially with advanced technologies such as combined heat and power (CHP) systems. CHP systems generate both electricity and proper heat, increasing overall energy efficiency. Coal-fired power plants typically have lower energy conversion efficiencies compared to biomass systems. However, technological advancements such as ultra-supercritical and integrated gasification combined cycle (IGCC) plants have improved coal plant efficiencies to some extent. Thus, the two processes also differ in terms of production and availability. Mixing biocoke with pure Coke is also possible using renewable biomass resources (El-Tawil et al., 2021). However, it is not the same as using biomass fuels. Biocoke fuel requires a transformation of the biomass first before adjusting the properties of the coal (Loison et al., 2014).

Biocoke differs from coke because the process involves combining various renewable and sustainable biomass resources (Loison et al., 2014). The solid fuel properties shown from this combination are fully presented in Table 1 (Antar et al., 2021; McKendry, 2002; Vávrová et al., 2022). Each of the characteristics assessed on the biomass material will result in the level of viability for biocoke. The high volatile matter content of biomass can increase biocoke's ignitability, which has a medium ignition level (Mizuno et al., 2016). The calorific value of biocoke is comparable to biomass and fossil pellet fuel (Cui et al., 2019; Ito et al., 2011; Liu et al., 2015). The calorific value of biocoke can range from approximately 20 to 30 (MJ/kg) or 8,500 to 13,000 BTU/lb. Biomass fuels, such as wood chips, pellets, or agricultural residues, can have varying calorific values depending on their moisture content, density, and specific composition. Generally, the calorific value of biomass ranges from around 15 to 20 MJ/kg or 6,400 to 8,500 BTU/lb. The calorific value of fossil pellet fuel can vary depending on the type and quality of the fossil fuel used. Coal pellets typically have a higher calorific value than biomass or biocoke. Calorific values for fossil pellets can range from approximately 25 to 35 MJ/kg or 10,700 to 15,000 BTU/lb. Meanwhile, biocoke has a higher fixed carbon content, making it more durable with high heat release than conventional biomass resources (Ito et al., 2011). Biocoke has a lot of resources because it can be reproduced using waste from photosynthetic plants or municipal mixed solid waste, as presented in the next sub-chapter.

2.1. Residue of agriculture

Agricultural residues as biomass for use as a heating energy generator have been investigated by Erdiwansyah et al. (2022), Ölz and Beerepoot (2010). In addition, rice straw biomass waste, wood biomass from plants, shell waste, durian fruit peel, palm oil solid waste, and other green wastes are also very suitable as raw materials for biocoke production (Abd Rashid et al., 2014; Florentino-Madiedo et al., 2019; Montiano et al., 2016; Suopajärvi et al., 2013). Banana peel and orange, synthesized into biocoke, showed high mechanical strength and had intense pressures reaching 167.0 MPa and 98.4 MPa with initial moisture levels of 0.52 wt% and 1.81 wt% (Murata et al., 2014). A different study stated that the ash content in cathode sawdust was around 13%. Biocoke raw materials have a higher potential than partial briquettes because they have high solids (Montiano et al., 2014).

The ash content obtained from the shell waste biomass is below 12%, so the shell waste raw material is also very suitable to be used as a biocoke production material so that the formation of slag during the iron production process can be avoided (Jha and Soren, 2017; Zandi et al., 2010). The ash content of the shell biomass waste is about 7–8 wt%. At the same time, the compressive strength and density reach 0.9 g/cm3 89–149 MPa when the temperature reaches 700 °C. The practical application of high-pressure biocoke fuels should have compressive forces of up to 60–200 MPa (Zandi et al., 2010). In addition, charcoal produced from shell biomass waste must meet mechanical and chemical requirements to meet requirements to become biocoke.

Similarly, the biomass sourced from the leaves of split trees, broccoli, and manganese seeds must also have high density and quality to become biocoke (Mizuno et al., 2011). Manganese seeds found in another study showed that the volatile matter removal rate obtained was higher, and the ignitability shown was the greatest. Meanwhile, the compressive strength of biocoke from broccoli is also considerable, reaching 130 MPa when the initial humidity comes to 5% with a production temperature of 413 K. The effect of the size of the biocoke specimen from green tea powder shows that its mechanical strength can be made with a diameter of 12 mm and produces biocoke specimens and high ultimate compressive strength of around 67 MPa (Mizuno et al., 2016). Meanwhile, the results of biocoke research with rice husk as raw material showed the highest heat compressive strength of 4.8 MPa with a process temperature of 973 K more elevated than other biomass materials. Fibre and silica can produce integrity with extra structure in biocoke made from rice husks (Mizuno et al., 2015).

Evaluation of the compatibility of vegetal and woody biomass for biocoke production has been studied by (Capela et al., 2022; Qin and Thunman, 2015). The evaluation results showed that the adherence of biocoke from waste bark, wood waste, and straw to coke quality decreased to 0.14–7.13 wt% with a charcoal mass of around 19.4–29.5%. Biocoke using Straw found by several researchers showed that combustion reactivity increased in the presence of high potassium content. Meanwhile, an investigation of pine wood biomass waste used as biocoke using an auger reactor has also been carried out (Solar et al., 2016). The findings were that the higher the pyrolysis temperature, the quality of the biocoke also increased, but with the presence of a secondary reactor that burned large charcoal, it decreased. Olive and Eucalyptus wood biomass used for biocoke synthesis under temporary gasification conditions with constant temperature has been studied by Diez and Borrego (2013). It can be reported that the resulting ash content is lower by around 0.17% and 0.55% by ignoring the sulfur content.

A different study reported that Japanese knotweed produced for biocoke with high compression and temperature yields a calorific value of about 17.9 MJ/kg and an ash content of about 7% (Nakahara et al., 2015). In addition, the biomass samples from weeds, citrus, vegetable coffee, and tea have a low ash content of about 10%, and sulfur and pre-treated dewatering show suitable compatibility for raw materials for biocoke production (Li et al., 2014). A study on Yellow Poplar applied as co-pyrolysis and hard and soft coking coal under non-isothermal and isothermal conditions was analysed (Jeong et al., 2014). The results showed that the fraction of biomass mixed with coal increased, causing the reaction kinetics to be high, and the energy activity produced from biocoke decreased. In addition, the macro-pore structure of the mixture of biomass and coal shows its suitability for

Table 1
Solid fuel characteristics.

Characteristics of biomass	Definition of biomass
Non-combustible stuff is scarce.	The non-combustible element will decompose into ash, lowering the HCV of the fuel.
Low-cost manufacturing	Continuous production should be inexpensive, necessitating an ample supply of feedstocks and a simple manufacturing procedure.
Combustion under control	This should produce heat at a reasonable rate without posing an explosion risk.
Low-cost storage	This should be simple to keep and inexpensive.
High-efficiency combustion	It also has a low ash concentration and no residue at the end of the combustion operation if the air-to-fuel ratio is correct.
The temperature of ignition: moderate	The ignition temperature is the lowest temperature at which the fuel must be preheated to begin burning smoothly. Fuel with a low ignition temperature readily catches fire, making it dangerous to store and carry. Kindling may be problematic if the ignition temperature is too high. As a result, the ignition temperature should be mild.
Unintentional combustion	This should not be spontaneous, as this could result in fire hazards.
High calorific value	When burned, it should generate a lot of heat. HCV is influenced by the nature of the fuel, particularly its water content.
Inert combustion products	Combustion waste should not be dangerous or polluting to the environment.
Transport is simple.	It should be simple to manage and inexpensive.
Moisture content is low.	Reduced moisture content is required because it affects HCV.

biocoke applications. Thus, it can be proven that the agricultural waste biomass obtained for biocoke production is a very suitable alternative fuel. This is because the results have different levels of variation for various applications.

2.2. Municipal solid waste

The biomass fraction mixed with MSW municipal solid waste and cardboard and paper waste can also be used as raw material for biocoke production. MSW biomass enhanced by hydrothermal technology is blended into solid biofuels for the co-combustion of coal with low chlorine content. Mixing MSW with coal can improve the fuel ignition system and volatile release (Yoshikawa and Prawisudha, 2014). Research through testing the synthesis of biocoke using farm compost and cardboard with pyrolysis has been investigated in Canada. The findings of cardboard raw materials that were carried out produced a larger biocoke of about 87.5%. At the same time, the pyrolysis temperature and calorific value can reach the optimum point of 250 °C (Ghorbel et al., 2015). In particular, the potential for green waste, newspapers, cardboard, and wood chips to be used as biocoke precursors was also investigated (Bansode et al., 2014). The study results show that MSW biomass is a promising raw material, especially for synthesizing biocoke. MSW biocoke produced from newspaper waste can be reached at 350 °C.

Meanwhile, biocoke from cardboard waste has a higher cation exchange capacity. In addition, high pyrolysis temperature can increase the ability of MSW-based biocoke for nutrition and water retention, as reported in the study (Rehrah et al., 2016). The growth of soil microorganisms, long-term carbon sequestration, and exchange processes in soil cations can be further enhanced.

The thermal and physical–mechanical characteristics of sawdust and cardboard waste biomass have been analysed in several studies. The chemical composition analysed showed a low weight and sulfur content of 0.062% and 0.088%. Meanwhile, the carbon content reaches 38.32%, and the weight is 43.4% when the mixing ratio is at the right time. In addition, the exhibited material's compressive strength and calorific value can result in lower ash content (Lela et al., 2016). The characteristics and synthesis of biocoke obtained from 18 lignocellulosic MSW biomass waste components were investigated (Mitchell et al., 2013). The findings showed that biocoke from newspaper biomass sources, construction wood waste, and paper towels had volatile materials and ash content. However, it has a higher fixed carbon content, so it is very suitable for supplementing carbon-deficient organic soils and is also young for carbon sequestration.

On the other hand, biocoke from green waste sources, paper, and cardboard can have a high ash content and is highly recommended for adding minerals to soil organics (Mitchell et al., 2013). Sawdust and cardboard waste biomass are very suitable as raw materials for biocoke production, as the results of several studies have been discussed previously. It can be concluded that agricultural residues and MSW are very feasible and proven to be used as a synthesis of biocoke fuel from various sources of biomass waste, as presented in Table 2 (A Adrados et al. 2015; Adrados et al., 2015a,b; Ghorbel et al., 2015; Jung et al., 2014; Mitchell et al., 2013; Mizuno et al., 2016, 2011; Montiano et al., 2014, 2013; Murata et al., 2014; Qin and Thunman, 2015; Seo et al., 2013; Solar et al., 2016; Tumutegyereize et al., 2016; Yoshikawa and Prawisudha, 2014).

Bio-coke, or biocarbon or biomass coke, is a solid fuel derived from biomass materials. The properties conducive to bio-coke synthesis can vary depending on the specific biomass feedstock and the desired end-use application. However, several general properties are desirable for bio-coke synthesis. Bio-coke should have a high carbon content to ensure efficient combustion and energy release. A high carbon content also contributes to the stability and durability of the bio-coke. Biomass feedstock used for bio-coke production should have low moisture content to minimize the energy required for drying and to prevent excessive volatile matter in the final product. Moisture content can be reduced through pre-treatment processes such as drying or torrefaction. Ash is the inorganic residue that remains after the combustion of biomass. A low ash content is desirable in bio-coke as it reduces the potential for slagging, fouling, and corrosion in combustion or gasification systems. Certain biomass feedstocks naturally have lower ash content than others. Fixed carbon refers to the non-volatile carbonaceous material in the biomass. Bio-coke's high selected carbon content contributes to its energy density and combustion efficiency.

Volatile matter is the portion of biomass that vaporizes and combusts during thermal conversion processes. While some volatile matter is necessary for ignition and combustion, an excessive amount can lead to emissions, decreased energy content, and reduced stability. Controlling the volatile matter content is essential for producing bio-coke with desirable properties. Biomass feedstock should be processed to an appropriate particle size for efficient pyrolysis or carbonization. The particle size affects

Table 2
Biomass energy potentials for biocoke conversion in different places worldwide are summarized.

Ref.	Energy potential of biomass (biocoke)	Different country
Hambali et al. (2016)	756.083	Indonesia
	811,839	Malaysia
Hambali et al. (2016)	337.582	Thailand
Bank (2012)	439,614	Myanmar
Leary et al. (2021)	139.169	Cambodia
Akgun et al. (2011)	25.735	Laos
	567,648–1576,800	India
Leinonen and Cuong (2013)	1346,400	Vietnamese
Kerdsuwan and Laohalidanond (2022)	23,368	Taiwan
Biofuels (2021)	152,360	Korea
Fernandez (2021)	146,500,000	China
Goto et al. (2011)	139,756	Japan
Sandu et al. (2010)	27,342	Australia
	3349,440	Russia
Chandraratne and Daful (2021)	2635,200	United States
	1256,040	European Union (EU)

the heating and mass transfer rates during synthesis. Biomass feedstock with low sulfur and nitrogen content is preferred for bio-coke synthesis to minimize sulfur dioxide (SO_2) emissions and nitrogen oxides (NOx) during combustion. Bio-coke is intended to be a more environmentally friendly alternative to fossil fuels. Therefore, sustainable and renewable biomass feedstocks, such as agricultural residues, energy crops, or forestry by-products, are essential.

Households, commercial establishments, and institutions generate Municipal Solid Waste (MSW). It typically consists of organic waste (food scraps, yard waste), paper, plastics, glass, metals, and other materials. MSW composition can vary based on urbanization, socio-economic status, and waste management practices. Industrial waste is generated from manufacturing, construction, and operations. It can include various materials like chemicals, solvents, heavy metals, sludge, and hazardous substances. Biomass waste can be utilized for energy production, such as biofuels, biogas, and biomass-based power generation, reducing reliance on fossil fuels. Effective waste management strategies aim to minimize waste generation, promote recycling and reuse, adopt appropriate treatment technologies, and encourage sustainable practices. The challenges and opportunities associated with different waste types vary, necessitating tailored approaches and integrated waste management systems for optimal waste reduction and resource recovery.

2.3. Biocoke raw material in Indonesia

Biomass waste from the agricultural sector is the most productive and contributes to its abundant availability as a raw material for producing biocoke fuels (Dash and Pati, 2018; DOSM, 2019; Perangkaan, 2013). Indonesia has significant renewable energy sources, especially in the agricultural sector, which can be used as raw materials for biocoke production (Erdiwansyah et al., 2020). Renewable energy sources from biomass sources exceed those in other Southeast Asian countries. In 2014 Malaysia's agricultural output increased by 6.0% compared to 4.7% in 2013, contributing to gross domestic product (GDP) of around 9.2% (Dash and Pati, 2018; DOSM, 2019; Perangkaan, 2013). The main contribution came from oil palm plantations at 46.8%, forest logging products at 7.8%, and rubber at around 6.7%. There was a significant increase in the planted area, which reached 16.7% or 2.3 thousand hectares for cocoa, 3.1% or 162.3 hectares of oil palm, 2.7% or 18.0 thousand hectares of rice, and 0.4% or 2.8 thousand hectares of rubber planted area (Dash and Pati, 2018; DOSM, 2019; Perangkaan, 2013). Meanwhile, durian, banana, coconut, guava, pineapple, jackfruit, and watermelon production increased by 100% in 2013 (Abdullah, 2002; Jingjing et al., 2001; Mahidin et al., 2020). Demand continues to grow for agricultural waste with a very high volume. The availability and sustainability of raw materials for biocoke production indicate this. In 2013 the energy potential of Malaysia's biocoke per year from agricultural waste reached 811,839 TJ.

Rice and palm oil residue biomass in 2013 is the primary raw material for biocoke production which can contribute as much as 15.78% and 78.96% with its abundant availability (Akhtar and Masud, 2022; Mariyono, 2014; Somasundram et al., 2016). Malaysia's global biomass energy potential accounts for 0.51% and 21.05% of Southeast Asia. Meanwhile, Indonesia has the potential for energy from biomass sources, reaching 32 GW to become a global energy centre. Biocoke energy potential can be estimated by multiplying agricultural residues divided by 100 by the total biocoke/TJ energy potential, especially farm residues. Comprehensively, the theoretical biocoke/biomass energy potential found in various countries can be shown in Table 2. The results indicated that the potential for agricultural residues in Indonesia and Malaysia has a level of contribution that can address renewable energy problems so that the production and utilization of conventional energy can be reduced.

2.3.1. Oil palm of biomass waste

The area of oil palm plantations continues to increase in line with the increasing production of palm oil biomass waste for biocoke production [96.97]. Palm oil milling process that produces lignocellulosic biomass waste such as empty fruit bunches (EFB), oil palm trunks (OPT), palm pressed fibre (PPF), oil palm fronds (OPF), and palm kernel shell (PKS) (Samiran et al., 2015). The results of oil palm biomass waste production in 2013 are shown in Table 3 (Abdullah and Sulaiman, 2013; Erdiwansyah et al., 2022; Matovic, 2013). In 2013 palm oil biomass waste produced as much as 91 million tons. Palm oil biomass waste can be used to reduce greenhouse gas emissions and fuel GHG emissions due to the decomposition of palm oil waste in landfills (Ko et al., 2017). Oil palm biomass waste production for calorific value analysis is presented in Table 3 (Nasrin et al., 2008). The potential energy from using agricultural residues through the biocoke synthesis can be obtained at 641,045 TJ.

2.3.2. Waste from cocoa

Biomass waste from cocoa pods harvested per tonne can produce around 750 kg more (Daud et al., 2014). The area of cacao plantations reached 18,427 hectares in 2015 and annually can produce up to more than 6700 t (DOSM, 2019). Meanwhile, the location of cocoa plantations in Indonesia in 2020 will reach 1,508,955 hectares and produce ± 60,500 kg/year of cocoa pod waste (Yuwono, 2020). The cocoa production level in Indonesia

Fig. 2. Indonesian cocoa production statistics (2015–2019).

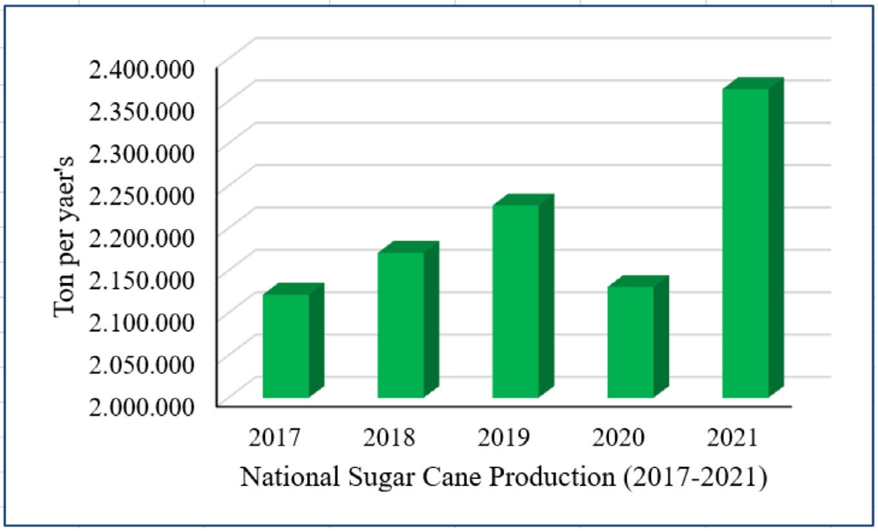

Fig. 3. Statistics of sugarcane production in Indonesia.

Table 3
Solid by-products from palm oil mills, as well as their moisture content and calorific values, are wastes from palm oil production (Abdullah and Sulaiman, 2013; Ling et al., 2015; Mangurai et al., 2018; Nasrin et al., 2008; Sadig et al., 2017; Sulaiman et al., 2016).

Quantity (in 1000t)	Calorific value (MJ/kg)	Moisture content (%)	Waste's
4506	20.11	12	VFD
11,059	19.07	37	PPF
18,022	18.84	67	EFB
10,827	24.90–31.16	47	OPT
46,837	15–20	70	OPF

in the 2015–2019 period is presented in Fig. 2. Therefore, annual production will continue to increase yearly. Meanwhile, the calorific value of biomass from cocoa pods is 17 MJ/kg, equivalent to the potential for biomass energy of 85 TJ/year (Syamsiro et al., 2012).

2.3.3. Sugarcane

In 2012, Malaysia produced 49,370 metric tons of sugarcane, released by the ASEAN Share Resilience Information System (AFSIS) (Briones and Felipe, 2013; Suhariyanto and Thirtle, 2001). Indonesia produced 978.9 thousand tons of sugar cane in 2020. The Ministry of Agriculture (Kementan RI) estimates that national sugarcane production will be 2.36 million tons in 2021. This increase is 2.58% from last year's 2.13 million tons (Luis and Moncayo, 2020). Statistics of sugarcane production in Indonesia for 2017–2021 are shown in Fig. 3. Each weight of biomass feedstock from bagasse can be converted and processed to be around 30%. Malaysia's annual bagasse production is approximately 14,811 tons, with a moisture content of 50%, almost equivalent to the total dry weight of 7406 tons/year (Faria et al., 2012). Dried bagasse has a calorific value of about 14.4 MJ/kg with an estimated energy potential of almost 107 TJ and above that can be produced using fuel energy from bagasse. Sugarcane waste biomass, such as shoots and leaves, comprised 68.5% of the total weight during replanting and harvesting. The calorific

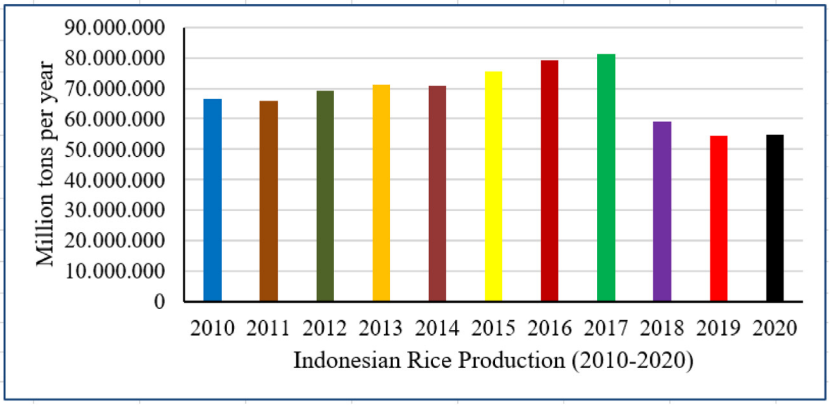

Fig. 4. Indonesian rice production statistics (2010–2020).

value of leaves and projections can reach around 17.39 MJ/kg [84]. Therefore, it can obtain energy of approximately 176 TJ for 2012 if utilized and produced in biocoke applications. Thus, the costs for solid waste management can be reduced.

2.3.4. *Rice husk and straw wastes*

Rice production in 2020 was 54.65 million tons of milled dry grain (GKG), an increase of 45.17 thousand tons or 0.08% compared to 2019, which was 54.60 million tons of GKG (Isnaeni Nur Khasanah, Octavia Rizky Prasety, Ika Wirawati, Nialita Rahmadhani, Retno Poerwaningsih, (Khasanah et al., 2021). If converted into rice for food consumption, rice production in 2020 was 31.33 million tons, an increase of 21.46 thousand tons or 0.07 percent compared to 2019, which was 31.31 million tons. The potential production for the January-April 2021 period is estimated to reach 14.54 million tons of rice, an increase of 3.08 million tons or 26.84% compared to rice production in the same surround last year of 11.46 million tons (Badan Pusat Statistik, 2022). The potential rice harvest area in the January-April 2021 sub-round reaches 4.86 million hectares or an increase of about 1.02 million hectares (26.53%) compared to the January-April 2020 sub-round, which amounted to 3.84 million hectares (Badan Pusat Statistik, 2022). Statistics and total rice production in Indonesia during the 2010–2020 period are shown in Fig. 4. The calorific value of rice straw and rice husks are around 15.09 MJ/k and 15.84 MJ/kg, respectively, which are abundant and very promising sources of biomass because they have ideal energy potential. In addition, rice residue can also be used as a precursor for biocoke production because it has low water content and is efficient.

2.3.5. *Waste of coconut*

The Central Statistics Agency (BPS) noted that coconut production in Indonesia will reach 2.85 million tons in 2021. This value is up 1.47% from the previous year's 2.81 million tons. The complete statistics on Coconut Production in Indonesia for 2011–2021 are shown in Fig. 5. Indonesia's coconut production has tended to decline in the last decade. Initially, Indonesia's coconut production amounted to 3.17 million tons. The figure also decreased 7.43% to 2.94 million tons the following year. Indonesia's coconut production rose 3.85 percent to 3.05 million tons in 2013. The increase only lasted a year. Indonesia's coconut production figure will continue to decline until 2020. Indonesia's coconut production will only increase in 2021 after falling for seven years.

Meanwhile, Riau is the largest coconut producer in Indonesia because it produces 395 thousand tons. After that, there is North Sulawesi, with a coconut production of 271.1 thousand tons. Coconut production in East Java is 244.5 thousand tons. Meanwhile, North Maluku and Central Sulawesi produced 211.8 thousand tons of coconut and 199.2 thousand tons, respectively. This article has been published on Data Indonesia titled "Indonesian Coconut Production Increases 1.47% in 2021" (Karnadi, 2022). The abundant coconut waste biomass can be converted into energy for sustainable fuel applications because the availability of coconut waste is adequate. The results of coconut biomass waste have different characteristics and calorific values for each unit weight of coconut production, as presented in Table 4.

Table 4
The yields of biomass waste and the calorific content of various coconut trash produced in 2015 [84].

The yield of Biomass mass (%)	Calorific value (MJ/kg)	Waste of coconut
4.9	15.39	EFB
16.1	17.86	VFD
22.5	16.02	OPF
36.2	16.22	Husk

2.3.6. *Waste of bananas*

If you look at the annual production from 2016, banana production will continue to increase until 2020. In 2019, there was a significant increase of 7,280,658 tons to 8,182,757 tons. Every year the production of the most superior bananas, but also in the production of fruit plants in each province in 2020 is the highest in the areas of East Java, Central Java, West Java, Lampung, and North Sumatra, each of which contributes to production The largest is in banana fruit plants. In East Java, banana production was 2,618,795 tons. Central Java was 798,599 tons, West Java was 1,263,504 tons, and Lampung was 1,208,956 tons (Arkandana, 2021). The complete statistics on banana production in Indonesia during the 2016–2020 period are presented in Fig. 6.

In 2020, the highest banana production occurred in the fourth quarter, reaching 2.36 million tons, with plants producing 83.50 million clumps. Provinces with the most significant banana production are East Java, West Java, and Lampung. East Java contributed 32% to national production, reaching 2.62 million tons, and plants produced 26.40 million clumps. West Java contributed 15.44%, with the show coming in 1.26 million tons and plants that made 20.05 million clumps. Lampung contributed 14.77%, with production reaching 1.21 million tons and plants producing 12.48 million clusters. Banana stem, leaf, and peel wastes have high calorific values, respectively 13.7 MJ/kg stem, 17.1 MJ/kg leaf, and 15.7% MJ/kg peel [88–90].

2.3.7. *Waste of pineapple*

Pineapple production in Indonesia was 2.45 million tons in 2020. Indonesia is one of the countries with the most significant

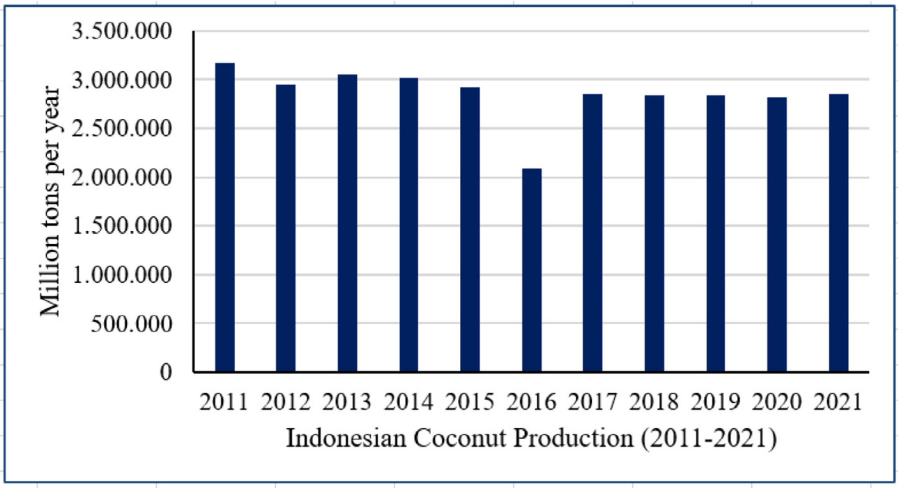

Fig. 5. Indonesian Coconut Production Statistics 2011–2021 Period.

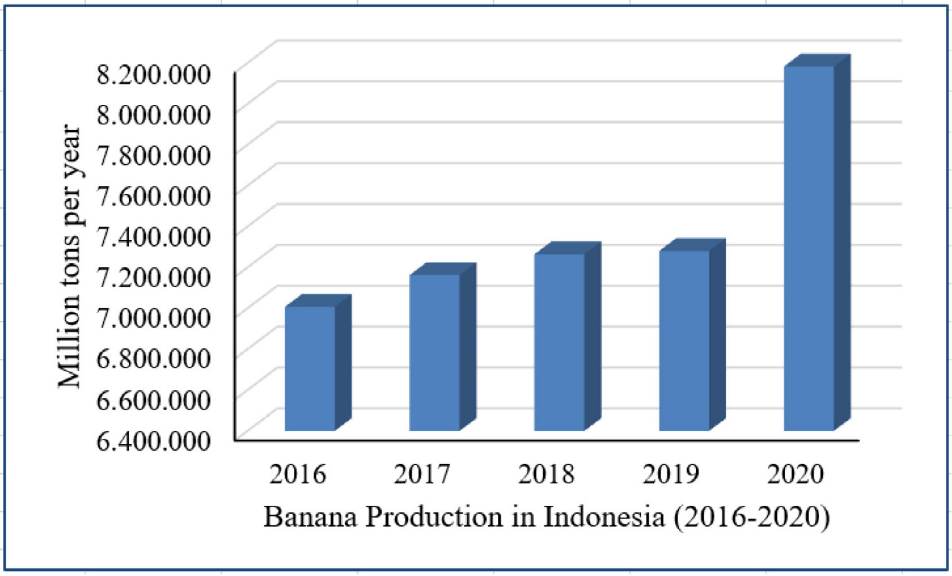

Fig. 6. Indonesian Banana Production Statistics 2016–2020.

pineapple production in the world. According to worldatlas.com, Indonesia ranked 9th as the largest pineapple-producing country in the world in 2018. It is not surprising that Indonesia's pineapple production increases yearly. In 2020, pineapple production in Indonesia reached 2,447.24 thousand tons. This production increased by 11.42% compared to the previous year, only 2,196.46 thousand tons. Provinces with the most significant pineapple production are Lampung, Central Java, and West Java. Lampung contributes 27.07% to national production. Plants produced in Lampung are 219.66 million clumps, reaching 662.59 thousand tons (Fakhri, 2021).

An increase follows the high production of pineapple in Indonesia in the value of exports. The export value of Indonesian pineapples has shown an increasing trend in recent years. According to BPS data, in 2020, the export value of pineapples in Indonesia will reach US$ 274,126 million. This figure increased by 34.49% compared to the previous year, which was only US$ 203,819 million. The high export of pineapple is thought to be due to the COVID-19 pandemic, which has made people pay more attention to their lifestyle by consuming nutritious foods. This aligns with the WHO recommendation to consume fruit during the Covid-19 pandemic. One of the fruits recommended by WHO for consumption is pineapple. Pineapple has a high vitamin C content. Vitamin C has an essential role in maintaining the body's immunity. Strong body immunity is needed during the current pandemic to fight viruses and bacteria that cause infection.

Some main destinations for Indonesian pineapple exports are the United States, the Netherlands, and Spain. The United States will be Indonesia's largest export destination in 2020. According to BPS publications, in 2020, Indonesia exported pineapples to the United States of 63.94 thousand tons with an export value of US$ 83.17 million. This figure increased compared to the previous year, with only 57.22 thousand tons for export volume and US$ 50.86 million for export value. Waste biomass from pineapple has a calorific value of 15.2 MJ/kg for pineapple peel and 18.9 MJ/kg for pineapple leaves, as reported by Some of the leading destinations for Indonesian pineapple exports are the United States, the Netherlands, and Spain. The United States will be Indonesia's largest export destination in 2020. According to BPS publications, in 2020, Indonesia exported pineapples to the United States of 63.94 thousand tons with an export value of US$ 83.17 million. This figure increased compared to the previous year, with only 57.22 thousand tons for export volume and US$ 50.86 million for export value. Waste biomass from pineapple has a calorific value of 15.2 MJ/kg for pineapple peel and 18.9 MJ/kg for pineapple leaves, as reported by Some of the leading destinations for Indonesian pineapple exports are the United States, the Netherlands, and Spain. The United States will be Indonesia's largest export destination in 2020.

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2.3.8. *Residues of wood*

A significant contribution of wood biomass waste is obtained from the results of panel products, logging, the furniture industry, and sawmills, as reported by Association of Southeast Asian Nations (2020). During the Covid-19 pandemic, the total production of natural forest (HA) and plantation forest (HT) logs in Indonesia for the 1st and 2nd quarters of 2021 increased by 6.20% compared to the same period in 2020. This increase was due to high demand, but the supply is somewhat limited, so that prices will increase, and wood production will continue to be boosted, so the growth is quite significant. The energy content generated from waste reaches 988.88 JT/million tons (Association of Southeast Asian Nations, 2020). The results are from wood residues from various processing and can be used as mangroves to produce biocoke as fuel for renewable power plants.

2.3.9. *Waste of corn*

Based on the predictive calculation report of the Data and Information System Centre (Pusdatin) of the Ministry of Agriculture, the national corn planted area in October 2019–September 2020 reached 5.5 million hectares (ha). The national corn harvested area from January to December 2020 reached 5.16 million ha. So, the prognosis for national corn production with a moisture content of 15% from January to December 2020 is entirely satisfactory, getting 24.95 million tons of dry shells, explained Kelvin. Therefore, the government's efforts to boost corn production provide maximum results to meet national needs. Based on data from the Pusdatin Ministry of Agriculture, the following are 10 provinces in Indonesia as the highest corn producers with a moisture content of 15 percent for January–December 2020. The first to third national rankings in 2020 did not shift compared to 2019 (Affandy, 2011). The biomass waste from corn leaves contains 32.1% by weight of cellulose, 18.1% by weight of hemicellulose, and 11.9% by weight of lignin (Amer et al., 2021). Corn leaf waste has a temperature range of 300–450 °C under a constant nitrogen flow rate.

2.3.10. *Municipal solid waste*

Indonesia produced 67.8 million tons of waste in 2020. Based on data from the Ministry of Environment and Forestry (KLHK), 37.3% of waste in Indonesia comes from household activities. The next most significant source of waste comes from traditional markets, which is 16.4%. As much as 15.9% of waste comes from the area. Then, 14.6% of waste comes from other sources. There 7.29% of waste comes from commerce. As much as 5.25% of waste is from public facilities. Meanwhile, 3.22% of waste comes from offices, as shown in Fig. 7. The average calorific value of municipal solid waste is around 9.12 MJ/kg, thus providing an enormous energy reserve each year for power generation fuel (Kathirvale et al., 2004; Khan et al., 2022; Lokahita et al., 2019).

3. Properties of biocoke

Biocoke energy is an alternative substitute for coal coke because it has the characteristics of the required and promising fuel. The complete comparison between the attributes of biocoke and coal coke is presented in Table 5. The calorific value contained in biocoke is comparable to that of coal coke in the range of 18–31 MJ/kg. Furthermore, biocoke has a shallow moisture content compared to direct biomass fuels. Biocoke has high flammability, low water retention, lower bulk density, low biodegradability, and homogeneous combustion characteristics (Cruz, 2012). Therefore, it is possible to control biocoke heating with high quality and better storage and transportation system characteristics. In addition, the combustion reactivity contained in biocoke is more moderate, and the combustion period is longer, with a higher energy density than biomass fuels (Rautiainen et al., 2012). This means that the compressive strength of biocoke is 38–149 MPa more increased than coal coke of 20 MPa. Thus, biocoke can withstand higher loads making it very suitable to be applied to steel blast furnaces even with extreme temperatures. The ash content in some biomass cokes is lower than that of metallurgical and foundry cokes such as Maple and Eucalyptus biocoke. Where these findings indicate that less slag is formed, has a high temperature, and carbon absorption increases in the presence of molten iron from metallurgical applications. The sulfur content in biocoke can be ignored to avoid potential contamination of pollutant and metallurgical emission products.

The production of biocoke fuel also has a lower price than biomass-based briquettes due to the lower energy consumption of the milling process (Fuchigami et al., 2016). However, the porosity shown in biocoke, and surface area is greater than that of pure coal fuel. This is because the volatile material contained in the biomass raw material is higher, so the pore formation is more significant because, during the pyrolysis process, flammable raw materials can be removed during the steel-making process. Further research on strategies to reduce the porosity of biocoke is urgently needed so that it can be applied appropriately to industry. The characteristics and potential of biocoke show similarities to coke and coal, especially in using adsorbents and activated carbon because the process is carried out with suitable physical and chemical activities. However, biocoke has a lower mechanical fluidity problem (Montiano et al., 2013). Thus, the defective rheology can affect the softening and melting of biocoke during the metallurgical process. In addition, it also affects the reaction of the metal ore and the quality of the final production. The comparison between conventional solid fuel and biocoke has a significant difference (Chaney, 2010; Chartier et al., 2013). The combustion temperature when using biocoke can reach 1300–1500 °C compared to 600–800 °C for wood pellets and 410 °C for wood chips. The burning time of biocoke is longer than that of wood pellets and wood chips. Meanwhile, biocoke burns faster than wood pellets and wood chips. As for clinker generations, biocoke is almost non-existent.

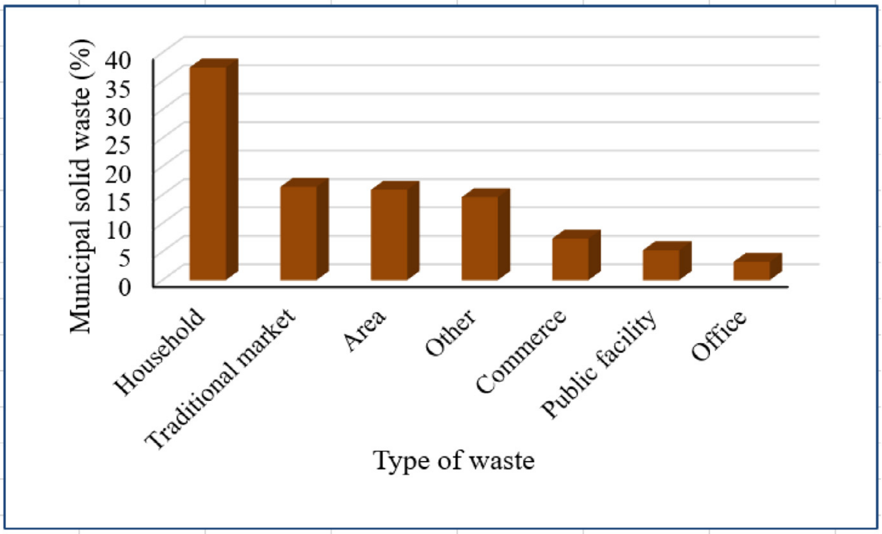

Fig. 7. Total municipal solid waste per type in Indonesia.

Table 5
Significant features of coal coke and biocoke compared (Information, 2015).

Functional of criteria	Biocoke	Rinks	Coke	Rinks	
The fluidity of Thermal (ppm)	Waste chestnuts	286–1336	–	1000–20,000	Montiano et al. (2014)
The Content of Carbon (wt%)	The Branch of Olive The Wood of Olive The Wood of Eucalyptus	81.1-85.7 86.0–94.5 88.0–90.1	–	90	Adrados et al. (2015a,b)
Calorific value (MJ/kg)	The Wood of Eucalyptus The Wood of Olive The Branches of Olive Japanese knotweed	31.0–31.6 28.8–30.8 27.1–29.0 17.9	–	29.29	Adrados et al. (2015a,b), Nakahara et al. (2015)
Sulfur content (wt%)	The Wood of Olive The Wood of Eucalyptus Maple wood	< 0.1 < 0.1 Negligible	Foundry Coke Metallurgical Coke	0.6–0.7 0.7	Adrados et al. (2015a,b), Cruz (2012)
Ash content (wt%)	Trimmed olive branch The Wood of Olive The Wood of Eucalyptus The Wood of Olive	9.2–12.8 9.2–9.5 5.9–6.2 0.39–1.63	Foundry Coke Metallurgical Coke	6–10 10–12	Adrados et al. (2015a,b), Cruz (2012)
Porosity (%)	Chestnut sawdust	51–54	Coke for Foundry Coke for Metallurgical	30–40 45–50	Montiano et al. (2014)
The Strength of Compressive (MPa)	Banana peel Orange peel Broccoli Leaf of a dead cherry tree mango seeds Green tea ground Cashew nutshell	98.4 167.0 130.0 38.0 57.0 67.0 89–149	MPa	20	(Jung et al., 2014; Mizuno et al., 2011; Murata et al., 2014; Zandi et al., 2010)

3.1. Properties of non-fuel

The carbon content in biocoke reaches 80–95 wt%, as in Table 5. In addition, the total surface area of the biocoke is also significant, between 160–240 m^2/g, especially hardwood biocoke and hardwood mixed biocoke, paper waste, and soft waste. The electrical conductivity for MSW biocoke reaches 2000–3000 s/cm when the temperature reaches 750 °C. While the surface charge reaches 2.0–2.5 mmol H+/g and 120–160 m2/g at a combustion temperature of 300 °C (Rehrah et al., 2016). The cation exchange capacity showed satisfactory results, especially for biocoke samples from cardboard, construction wood waste, paper, and green waste, and alkalinity of 84.5–218.2 mmol/kg (Kerdsuwan and Laohalidanond, 2022; Tun et al., 2019). Biocoke can be converted into soil because it has non-material properties to increase the organic carbon content in the ground. In addition, it can increase the ability of cation exchange and soil water retention, reduce nitrogen leaching, and neutralize soil pH (Dai and Ren, 2013; Dai et al., 2014). The stability and biodegradability of biocoke is an ideal choice, especially for soil carbon sequestration, so that the mechanical integrity of the soil can be strengthened (Dai et al., 2014).

3.2. High environmental sustainability

Biocoke production can use various agricultural waste and photosynthetic plants (Information, 2015). Thus, the processing and production of biocoke from agricultural waste is efficient for energy recovery. This is because the output of biocoke is sustainable with the low cost of mangroves, its availability is relatively abundant, and the potential for waste treatment to generate additional income (Agamuthu, 2009; Antonio et al., 2021; Boom Cárcamo and Peñabaena-Niebles, 2022). Meanwhile, conventional biomass combustion can still produce waste or ash (Jenkins et al., 1998; Lasek et al., 2017; Škrbić et al., 2020). Meanwhile, the synthesis of biocoke can effectively reduce the residual production of clean waste. This is because the conversion of gaseous, solid, and liquid fuels can be entirely changed by pyrolysis (Adrados et al., 2015a,b).

3.3. *High biomass energy retention*

The biocoke production process does not experience weight loss at the start and after it becomes a product (Ida et al., 2012). For example, with empty fruit bunches (EFB), the initial weight is 10 g, and after becoming biocoke, the importance remains 10 g. Thus, for the biocoke process, it is very suitable to do with the abundant availability of biomass. Biocoke fuel based on biomass has low atmospheric emissions, so that it can be used as an alternative to fossil fuels (Montiano et al., 2016).

3.4. *Insight and comparative analysis*

The results of studies on biocoke's characteristics and raw materials, in general, have been discussed and reported by (Mansor et al., 2018). Most of the residual biomass from agricultural products is used for biocoke production. The test results show a low % ash content of 12%, especially for sulfur and wood biomass. Thus, applying the coking process can effectively reduce sulfur dioxide emissions and prevent slag formation. In addition, the biomass feedstock has a high volatile matter of about 65%–80% higher than coal, so the pyrolytic reactivity of the biomass and the kinetics of coke can be improved. However, on the contrary, the oxygen content in the biomass is higher due to the presence of a lignocellulosic ether functional group which can damage the fluidity properties of the biocoke. Therefore, Biocoke production can result in low quality and cannot be processed through thermal pre-treatment. Therefore, future research, especially for the development of additives, is needed so that the mechanical fluidity of biocoke can be further improved.

The results of a recent study discussing MSW on the importance of hydrothermal processing for hydro-char production, especially for coal cofiring, have recently been carried out. However, there is a high moisture content, so further drying is required before applying to practical fuels. Biocoke from MSW has demonstrated suitability for activated carbon and soil amendment applications. Thus, translational research to suppress the actual implementation is highly recommended so that the application of biochar from MSW can be further developed. Therefore, future research, especially for the development of additives, is needed so that the mechanical fluidity of biocoke can be further improved. The results of a recent study discussing MSW on the importance of hydrothermal processing for hydro-char production, especially for coal cofiring, have recently been carried out. However, there is a high moisture content, so further drying is required before applying to practical fuels. Biocoke from MSW has demonstrated suitability for activated carbon and soil amendment applications. Thus, translational research to suppress the actual implementation is highly recommended so that the application of biochar from MSW can be further developed. Therefore, future research, especially for the development of additives, is needed so that the mechanical fluidity of biocoke can be further improved. The results of a recent study discussing MSW on the importance of hydrothermal processing for hydro-char production, especially for coal cofiring, have recently been carried out. However, there is a high moisture content, so further drying is required before applying to practical fuels.

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Biochar and biocoke are carbon-rich materials derived from biomass but differ in their production methods, intended applications, and chemical properties. Here are the critical differences between biochar and biocoke:

a. Production Method
Biochar is produced through pyrolysis, which involves heating biomass without oxygen. This process leads to the decomposition of biomass into solid carbonaceous material. Biocoke, on the other hand, is produced through a process called carbonization or coking, which involves heating biomass in the presence of limited oxygen. This process forms a solid fuel with a higher carbon content than the original biomass.

b. Purpose and Applications
Biochar is primarily used as a soil amendment. It is known for improving soil fertility, retaining moisture, enhancing nutrient availability, and sequestering carbon in the soil.

Biochar can be applied in agriculture, horticulture, and ecological restoration projects. Biocoke is mainly used as a fuel source. It is often utilized as a substitute for coal or coke in industrial processes such as steel production, foundries, and heating applications. Biocoke's high carbon content and energy density make it suitable for combustion or as a reducing agent in various industries.

c. Chemical Properties
Biochar is characterized by its high carbon content and porous structure. It contains stable carbon compounds, which means it decomposes slowly in the environment. Biochar typically has low ash content and can retain moisture and nutrients due to its porous nature. Biocoke has a higher carbon content than biochar, often exceeding 90%. It has a denser structure and higher energy content, making it a suitable fuel source. Biocoke can contain volatile matter, sulfur, and other trace elements depending on the biomass used and the carbonization process.

d. Environmental Impact
Biochar has potential environmental benefits, such as carbon sequestration in soils, improving soil health, and reducing greenhouse gas emissions. Its use can contribute to sustainable agriculture and mitigate climate change. Biocoke can be considered a more environmentally friendly alternative to fossil fuels when derived from sustainable biomass sources. It can help reduce greenhouse gas emissions and dependence on non-renewable resources. However, the carbonization process may produce some emissions depending on the efficiency of the process and the control of pollutants.

Overall, biochar and biocoke serve different purposes and have various applications. Biochar is primarily used for soil improvement and carbon sequestration, while biocoke is a fuel source in industrial processes.

4. Technology of biocoke

Metallurgical biocoke applications are still minimal, especially for bio-reducers in the clean-making process, because they have a rich carbon source [97]. In addition, low reactivity, low sulfur, low ash content, and high mechanical strength. The technical complications biocoke shows can replace up to 30% of coal coke for the iron casting process. In addition, it can supply heat and provide mechanical support for the iron content in the furnace, and the decarburization reaction can be initiated (Montiano et al., 2016). Continuous heating of biocoke can produce high temperatures around 600–1200 °C. Biocoke can also generate heat to replace coal-coke during the forging process, where the plastic deformation of metallic materials can be formed with specific dimensions on machine compression (Ida et al., 2012). Biocoke is also a very competent energy source, especially for gasification fuels and direct smelting furnaces, with a substitution rate of 50% (Uchiyama et al., 2014). Biocoke from MSW hydrothermal processing has also proven to be very suitable when burning with coal simultaneously (Yoshikawa and Prawisudha, 2014). Therefore, it can be used as an energy source for power generation.

Extensive research leading to the use of biocoke as a soil amendment agent has the potential to increase yields, agricultural sustainability, and viability. Biocoke from rice husk biomass sources can improve soil aggregation, water retention, clay, cation exchange capacity, and flow properties of sandy soils, as reported in Sri Lanka (Gamage et al., 2016). Biocoke amendments from cultivated rice husks have helped stabilize soil carbon and reduce nitric oxide emissions. In addition, the effects of greenhouse emissions caused by agricultural activities can also be reduced (Nguyen et al., 2016). The retention of soil ions and ammonium also has the potential to biocoke, which can increase the availability of phosphorus in the soil (Pratiwi et al., 2016). In other cases, biocoke sourced from rice husks for nitrogen fertilizer can also increase agricultural yields, especially in the lowlands, without significant changes in soil quality (Munda et al., 2016).

Biocoke production is also beneficial in environmental management. Applying husks for biocoke production to activate steam in decontamination and wastewater contamination can remove 82% glyphosate with optimal pH (Awasthi, 2022; Herath et al., 2016). Biocoke produced from rice husks is higher than tea leaves, especially in the efficiency of carbofuran separation with a balanced absorption capacity of up to 25.2 mg/g (Tan and Hameed, 2017; Vithanage et al., 2016). Biocoke from rice husks has also been shown to have efficiency in removing cadmium with a high moisture content of 95%–97% (Liu et al., 2022; Prapagdee et al., 2016; Yin et al., 2021).

5. Technologies for producing biocoke

Many technological developments, especially for thermal conversion, have been carried out to produce biocoke from biomass sources. The most common technological developments widely carried out are intermediate pyrolysis, slow pyrolysis, hydrothermal carbonization, fast pyrolysis, carbonization, and microwave pyrolysis (Mašek et al., 2016).

The heating rate in slow pyrolysis is obtained with a slower time between 0.1–100 °C/min to reach the peak temperature and has a longer residence time for the biomass charring process (Basu, 2018). Processed thermal decomposition can delay the interaction of the pyrolysis gas, solid and liquid products. Furthermore, biocoke production can be increased by secondary char formation with minimal sacrifice from the pyrolytic liquid yield (Mašek et al., 2016). The biocoke synthesis process with 25%–35% yields is very suitable for slow pyrolysis (Ding et al., 2016; Qi et al., 2022). Standard technologies with slow pyrolysis include drum pyrolysis, auger pyrolysis, vacuum pyrolysis, rotary kiln, and flash carbonization [96]. A summary of slow pyrolysis, a pilot in an industrial plant, is shown in Table 6 (Eriksson et al., 2015; Gustafsson, 2013; Jahanshahi et al., 2013; Zajec, 2009).

A heating rate of 100 °C/min and above is carried out by fast pyrolysis. Fast pyrolysis has a temperature range between 400–600 °C, achieved in a shorter time of 0.5–2.0 s. Rapid pyrolysis is generally processed compatible at a more significant fraction than the pyrolysis product of the cooled liquid (Mašek et al., 2016). Pilot studies commercialized with various fast pyrolysis technologies are presented in Table 7 (Bashiri et al., 2021; Kota et al., 2022; Lynch and Reno; Marshall et al., 2014; Strezov and Evans, 2014).

5.1. Pyrolysis of intermediate

Medium pyrolysis technology is the heating rate that has residence time between slow and fast pyrolysis. This intermediate pyrolysis technology can enable charcoal catalysis to improve the quality of liquid pyrolysis products. This process can reduce the water content, reduce the organic fraction, and increase the calorific value (Abnisa and Alaba, 2021; Mong et al., 2022; Yang et al., 2014). Therefore, the patented pyrolysis reactor with the development of a Pyro-former with a capacity of 20 kg/h, a height of 1.80 m, and a diameter of 0.20 m has been carried out by Yang et al. (2014). The pyrolysis facility developed in this work includes a pilot scale with a screw pyrolysis reactor recycled with internal charcoal to heat and catalyze reactions in secondary cracking (Yang et al., 2014). The developed technology can produce 28.5–30.1% biocoke and higher bio-oil, reaching 49.0–54.3% with biomass input of barley straw and wood (Yang et al., 2014).

Table 6
A global overview of slow pyrolysis technology, including case studies on the pilot and full-scale plants.

The technology of slow pyrolysis	Plant of industrial	Description	Ref.
Pyrolizer for Auger	Austrian PYREG twin-screw pyrolizer; 1000 t of capacity per year; Particle size of the feedstock must be under 30 mm, and the moisture content must be under 50%; 150 kW of output power; Dimensions: 40 ft; and cost up front: US$400,000	An auger is used to move the biomass feedstock through the pyrolysis zone. Heat is added externally or with a heat carrier, such as sand, a metal sphere, etc.	Gustafsson (2013)
Pyrolysis of Vacuum	The Carbonizes, a commercial vacuum pyrolysis unit owned by Prairie Biogas Ltd.; 15–100 t/day of capacity; Cost of capital: US$2.5–3.5 million; and yield: 250–350 kg of biocoke and 200–500 L of bio-oil per tonne of feedstock.	Vacuum is produced by continuously removing the pyrolysis gas, which is done at 450 °C and 15 kPa; Low heat transfer, short vapour residence time, and dispersion of the products were consistent with the outcome of slow pyrolysis; and appropriate for producing biocoke and ability to handle biomass feedstock with large particle sizes.	Dunne et al. (2008)
Pyrolizer of Drum	Melbourne's Pacific Pyrolysis Commercial Facility; 8000–16,000 t of yearly capacity; and Cost of capital: US$ 8 to US$ 15 million	As the biomass feedstock is paddled through the cylindrical reactor, heat from the outside causes it to break down thermally; High residence time is necessary, and heat is generated for the pyrolysis process using non-condensable pyrolysis gases.	Capp et al. (2019)
Kiln of Rotary	Italian university's rotary kiln pyrolysis pilot plant; Dimensions: 2.5 m long and 1.5 m wide; Range of power: 30–100 kW; Speed of the screw conveyor is 3 rpm; Source of heat: 8.4 kW of electric shells; and Mass output of biocoke: 41.6%	Gravity drives the rotation of the revolving kiln (reactor) for the biomass feedstock, and Around 5–30 min are spent at home.	Zajec (2009)
Carbonizer of Flash	Clayton, Victoria's CSIRO Pyrolysis Pilot Plant; Dimensions: 2.75 m high and 0.6 m in height; 100–300 kg/h of capacity; and 30% mass output of the good.	Under aerated, intense pressure and a packed bed with flash fire, biomass is pyrolysed.	Jahanshahi et al. (2013)

Table 7
The various pyrolysis of technologies.

Technology for quick pyrolysis	Plant of industrial	Description	Ref.
Reactor with a rotating cone	Commercial facilities for Enzym Red Arrow Rapid Thermal Processing (RTP); 40 t/day of capacity; Biomass: Wood scraps; 100 t/day of power; Wood waste as a feedstock; 5–6 wt% moisture content and 0.125–0.25 in. particle size for the feedstock; and yields 70% bio-oil, 15% gas, and 15% biocoke.	Pyrolysis products and the heating medium, or sand, sprout and are then collected by a cyclone and returned to the combustion reactor; Sand serves as a heat transporter when char is burned in the combustion reactor to heat the process.	Lynch and Reno
Screw/Auger of reactor	Ottawa, Canada's ABRI-Tech mobile auger pyrolizer; 50 t/day of capacity; Biomass: Waste wood; and 44–62 wt% bio-oil is produced in the yield.	Pre-drying and hot steel shot heat transfer mechanisms may be involved.	
Fluctuating fluidized bed	The Commercial Mobile Facility of Agri-Them Inc.; 10 dry tonnes of capacity per day; Energy sources: corn stover; Condition of the feedstock: 20% moisture content; energy independence by pyrolysis vapour combustion energy recovery; 2.19 wt% gas, 61.6 wt% bio-oil, and 17.0 wt% biochar was produced; Capital expenditure: US$1,500,000; Operating expenses: US$863,500; and Income: US$543,000	By fluidizing the gas flow velocity, char and vapour residence durations can be adjusted; To facilitate effective temperature management, fluidization homogenizes the temperature distribution; and since no particles are sprouted during the collection of the char from the pyrolysis bed,	Marshall et al. (2014)
Alternate pyrolysis	The Netherlands-based commercial ablative pyrolysis facility of Biomass Technology Group; has 250 kg/h of capacity, and Wood is an example of biomass.	Large biomass pieces (such as wood) are pyrolysed directly with the reactor wall while mechanically moving to allow complete contact between the biomass and the pyrolysis zone.	

Table 8
Microwave pyrolysis pilot plants: a summary.

Specification	Location	Scale	Feedstock	Ref.
100–150 kg/h capacity; 70% of recovered glass fibre, 17% of pyrolysis oil, and 13% of gas make up the yield; and 60 kW of microwave power.	Sweden	A test plant	Plastic bonded with recycled glass fibre (shredded wind turbine blade)	Metall (2012)
(4.5 kW) of microwave power; (46.88 wt%) gas, (30.16 wt%) liquid, and (22.96 wt%) biocoke in a corncob at 1 kW; (10 kg/hr) of capacity; Canola at 1 kW has (32.72 wt%) biocoke, (23.64 wt%) gas, and (43.64 wt%) liquid; (69.3 wt%) biocoke, (14.36 wt%) gas, and (16.34 wt%) liquid in corncob at 300 W; and (79.72 wt%) biocoke, (7.52 wt%) gas, and (13.76 wt%) liquid in canola at 300 W.	United States	A test plant	Corncob and canola as feedstocks	Karunanithy and Muthukumarappan (2011)

Table 9
A summary of some of Japan's commercial hydrothermal treatment plants.

Scale	Continuous commercial plant	Batch commercial plant
Location/Developer	Tokyo Tech, Japan	
Feedstock	Solid municipal waste (MSW)	
Specification	100 t/day of capacity; Condition of the feedstock: 65% moisture content; 100% mass yield; Capital expenditure: US$3 million; and Operating expense: US$0.15 million annually	1 t capacity per batch; conditions: 2 MPa and 200 °C; Living time: one h; 18–22 MJ/kg of calorific value; and volume reduction of 75%–80%;
Ref.	Yoshikawa (2013)	Jin (2014)

5.2. Pyrolysis by microwave

Fast, slow, and medium pyrolysis of biomass raw materials can be treated using microwave technology (Prapagdee et al., 2016). This technology differs from the others because it does not rely solely on convection and conduction for heat transfer. Microwave pyrolysis can promote volumetric heating of biomass particles and nuclei rather than pyrolysis (Prapagdee et al., 2016). Safety problems and high costs still hamper the increased operational efficiency of microwave pyrolysis implementation (Prapagdee et al., 2016). Some of the developed studies related to microwave pyrolysis are presented in Table 8.

5.3. Carbonization by hydrothermal means

Processing biomass raw materials in humid areas with temperatures between 150–350 °C resulting from water evaporation in a closed reactor for co-firing production can use HRC (Prapagdee et al., 2016). The advantage of HTC is that it can increase carbon retention by up to 80%. In addition, it can also increase the energy content of biomass because it only releases one-third during the process. The tolerance of water content in raw materials is also high so that the stability of the biocoke produced is more excellent (Prapagdee et al., 2016). The installation system for hydrothermal treatment, commercialized in Japan, is more concisely presented in Table 9.

5.4. Carbonization with the help of pressure

Several technologies regarding pressure carbonization have been submitted for patents. The study of one-dimensional stable combustion sourced from high-density biomass briquettes, in particular, has been carried out by Diez and Borrego (2013). The procedure for producing biocoke has been granted a standard patent with 4088933 (Mizuno et al., 2011). This technology describes the Japanese crushing knotweed at a specific size. In addition, it is also for the compression and compaction of particles in cylindrical moulds of any particular size. The production process is carried out through heating and cooling at a maximum room temperature so that experiments can be continued in a different method that has been patented under number WO2012164162A1 that the first thing to do is to remove mechanical impurities from the biomass feedstock. The pre-draying and pre-comminating processes aim to remove the water content in the biomass feedstock.

Furthermore, the refining of the biomass mangroves so that they become smooth and dried. The final process is the application of carbonization in raw materials to produce biocoke. While the basic implementation is the same as before, other ways exist to create and store biocoke. The biocoke production process must use standard machines and predetermined operating procedures (Metsärinta, 2012). As applied in Malaysia, palm oil extraction results such as EFB can be used for raw materials for projects developed through Nippon Steel Engineering technology. The compaction process of waste into a specific form can be carried out through a compression and heating process to be carbonized to produce biocoke eventually.

The research collaboration between Kindai University and Osaka Gas Engineering focuses on converting palm oil biomass waste for more efficient biocoke production. Research on biocoke production has been conducted at Kindai University in Japan since 2011 (Fuchigami et al., 2016). In 2014, a study was developed in Malaysia with the same research team to investigate waste oil palm empty fruit bunches as the primary raw material in biocoke production (Information, 2015). Based on the study's results, it was reported that OPEFB has enormous potential to be used as raw material for biocoke production. This study provides several methods to apply biomass as a raw material for biocoke production. In more detail, the process and flow for biocoke production are presented in Fig. 8. Biocoke production can be carried out by crushing biomass into prepared containers. The pressure and heating in the container are set under certain conditions. The conventional method must require heating up to 800 °C for carbonization.

Meanwhile, the transformed compaction technology developed at Kindai University can be carried out at 180 °C at 20 MPa

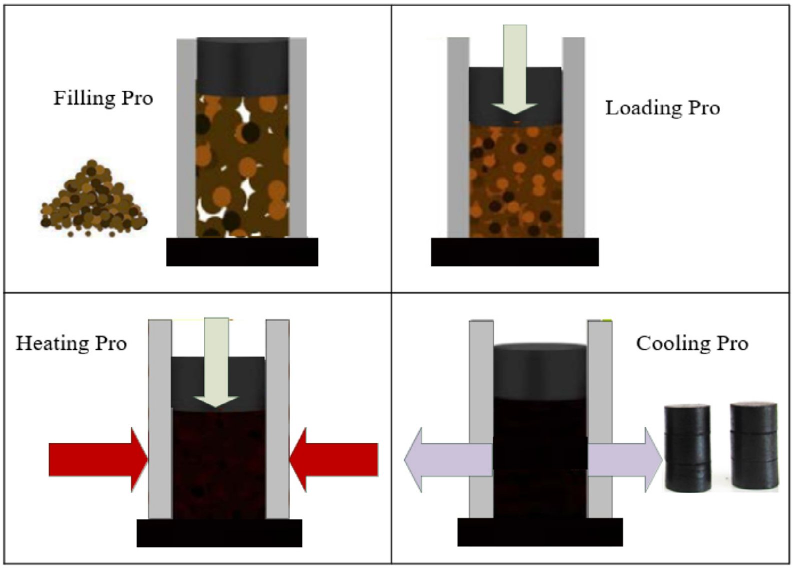

Fig. 8. Process production of biocoke (Mizuho, 2017).

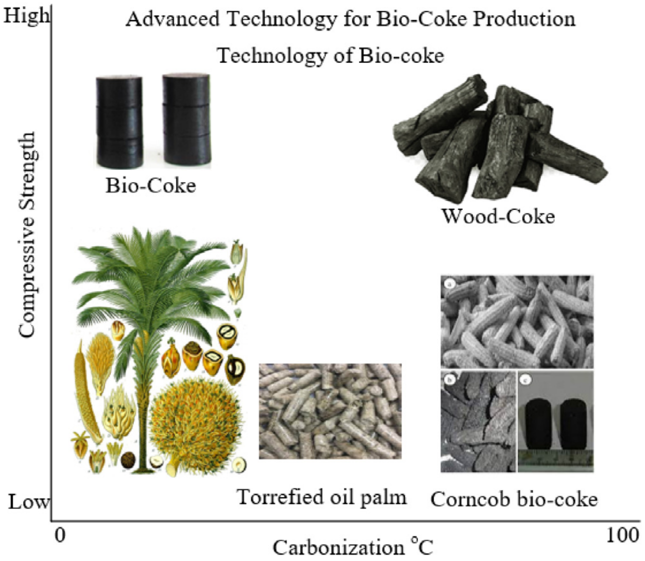

Fig. 9. Correlation between mechanical strength biocoke and carbonization (Mizuho, 2017).

(Fuchigami et al., 2016). This is done to lower the operating temperature so that a higher pressure can be achieved during biocoke production. In addition, volume loss and carbonization in raw materials can be minimized. Biocoke production with higher pressure levels is shown in Fig. 9.

Different pyrolysis methods impact the products and are applicable in different scenarios. Slow pyrolysis involves heating biomass at a relatively low temperature and slow heating rates. It produces a higher proportion of biochar and a lower yield of liquid and gas products. The biochar obtained has a higher carbon content and is more stable. Slow pyrolysis is suitable for applications where biochar production is the primary goal. It is commonly used in soil amendment, carbon sequestration, and biochar-based products. Fast pyrolysis involves rapid heating of biomass at higher temperatures, typically in the range of 400–600 °C. It produces a higher yield of liquid bio-oil and smaller amounts of biochar and non-condensable gases. The bio-oil obtained is rich in organic compounds and can be further processed for various applications. Fast pyrolysis is suitable for applications where liquid bio-oil is the desired product. It finds use in producing renewable fuels and chemicals as a bio-refinery feedstock.

Torrefaction involves the mild pyrolysis of biomass at temperatures typically ranging from 200–300 °C. It primarily produces solid biofuel, called torrefied biomass, with improved properties such as increased energy density and grindability. Torrefaction is suitable for biomass upgrading and densification. It can be used to produce solid biofuels for co-firing with coal, as a feedstock for gasification, or as a replacement for traditional biomass fuels. The choice of pyrolysis method depends on the desired product, process economics, and the specific application. Factors such as heating rate, temperature, and residence time determine product composition. Feedstock availability, energy requirements, and environmental impact also influence the selection of the appropriate pyrolysis method for a given scenario.

6. Biocoke development in Indonesia: Key challenges and prospects

6.1. Biocoke development prospects

One of the most critical agendas in developing Indonesia's energy sector and globally is biocoke. The local power generation and metallurgical industries are the ones that consume the most energy sourced from coke and coal (Commission, 2015; Tenaga, 2019). One of the highest countries that consume energy from biomass sources is Malaysia which reaches 630,825 TJ, equivalent to 77.77% of the existing biomass potential. Meanwhile, Indonesia is one of the countries with the highest biomass potential in Southeast Asia and even the world. This shows that the use of technology to use biocoke has led to the level of commercialization at the local level. Indonesia can be one of the strategic locations for producing biocoke because it has an extensive agricultural area and is a pillar of the economy. The results of agricultural waste in Indonesia annually reach thousands of tons generated from supply and demand chains such as palm oil, rice husks, sugar cane, pineapple, corn, and other agricultural wastes. Using renewable energy sources from biomass that can be reused can significantly reduce the amount of garbage. In addition, using biomass in renewable energy can also increase the secondary economy through biomass production. Biocoke energy will be one of the competitive and promising energy alternatives in the future so that the depletion of conventional coal raw materials can be reduced (Renn and Marshall, 2016). In addition, biocoke also has enormous benefits in reducing energy dependence on fluctuations in fuel prices and increasing national energy security. The identification of gaps in the development and improvement and development of biocoke production technology is the most discussed in several previous studies. The introduction of more reliable and adaptive technologies and the expansion of the area for potential applications of biocoke have also been widely discussed.

6.2. Commercial of barrier

Bio-coke production in Indonesia has not received the same trust as in developing countries such as Japan, the United States, and other European countries, especially in the metallurgical and steel-making industries. This is because the availability of fossil fuels is still abundant, and the cost of fossil fuels is still a mainstay. The Japanese research team has been actively conducting research in biocoke production. Meanwhile, in Indonesia, only a few researchers have developed pilot-scale facilities. Meanwhile, Malaysia has been developing bio-coke with the target of commercialization and export to Japan (Information, 2015).

Meanwhile, Indonesia's bio-coke production has just been researched on a laboratory scale and is planning the level of commercialization for the long term with the target of utilizing palm oil solid biomass waste and will export palm oil shells to Japan. This is based on the unavailability of raw materials in Japan, so it can be suggested as the primary raw material in producing biocoke because it has a lower price. Therefore, this kind of effort is expected to provide great opportunities and expand the availability of supply and demand for biocoke by involving several industry players at both local and national levels.

6.3. Technology of barrier

Although commercial viability has been limited, the demand for fossil fuels, coal, and coke is still very high. In addition, implementation barriers to the use of bio-coke are caused by technical constraints. Therefore, the collaborative system of several researchers between universities can provide better solid biomass feedstock for bio-coke synthesis. Good technical skills can crack and operate factories for bio-coke production on a commercial scale. There are currently no facilities for producing bio-coke commercially in Indonesia, so building a supply chain with adequate availability is impossible. Practical applications of bio-coke are also not yet available in either significant modification or high-pitched kiln facilities for bio-coke production (Ng et al., 2011). Making commercialization-scale research transitions with various innovations is a challenge for researchers in the future.

7. Discussion

Indonesia boasts significant biomass resources, including agricultural residues, forest residues, palm oil waste, and municipal solid waste. This abundance gives Indonesia a comparative advantage in biocoke production compared to countries with limited biomass feedstock availability. However, it is essential to assess the sustainability of biomass sourcing to avoid negative impacts on food security and ecosystems. One of the critical advantages of biocoke is its reduced carbon footprint compared to fossil fuels. However, the environmental effects of biomass sourcing, such as deforestation or excessive land use for energy crop cultivation, must be carefully evaluated. Comparative analysis can assess biocoke production systems' sustainability and environmental performance in different countries, including their greenhouse gas emissions and potential for mitigating climate change.

Government policies and regulations play a crucial role in promoting the development and deployment of biocoke fuels. Comparative analysis can examine other countries' policy frameworks and incentives, assessing their effectiveness in supporting biocoke production. This evaluation can help identify policy gaps in Indonesia and propose recommendations for fostering a favourable environment for biocoke fuel production and utilization. The demand for biocoke fuel varies across countries depending on factors such as industrial requirements, energy infrastructure, and societal acceptance. Collaboration and knowledge exchange between countries can accelerate the development and adoption of biocoke fuel technologies.

Biocoke fuel has a lower carbon footprint compared to fossil fuels. As awareness grows of the need to reduce greenhouse gas emissions and tackle climate change, the demand for low-carbon fuels is growing. Biocoke can be an attractive alternative to replace fossil fuels in the industrial and transportation sectors. Over-reliance on fossil fuels presents risks to energy sustainability and price volatility. Diversification of energy sources is essential to reduce these risks. Biocoke can be part of a more diversified energy portfolio, helping reduce dependence on fossil fuels and providing a more sustainable alternative. Biocoke can be produced from biomass waste, including agricultural waste, wood waste, palm oil waste, and community waste. Biocoke can help reduce waste problems and create added value from previously neglected resources by utilizing this waste as a feedstock.

Biocoke can be used in industry as an alternative fuel to improve energy efficiency. The torrefaction process to produce biocoke can change the properties of the biomass and remove moisture and volatile compounds, resulting in a more consistent and efficient fuel. The use of biocoke can help reduce energy consumption and improve industrial performance. Using biocoke fuel also encourages technological development and innovation related to the production process. Much research and development is being carried out to increase efficiency, reduce production costs, and improve the quality of biocoke. This creates opportunities for technology companies, researchers, and innovators to contribute to developing better solutions in the future. However, the use of biocoke still faces several challenges. Among them are competitive production costs, logistics infrastructure, sustainable biomass availability, and the necessary support policies. To maximize opportunities for the use of biocoke fuel in the future, cooperation between the government, the industrial sector, researchers, and the public is needed to create a conducive environment for developing and adopting this technology.

8. Policy and practical implications

Based on the results of the existing review, some policy and practical implications from current and future biocoke studies can be made as follows:

a. Environmental Benefits.
   Biocoke, being derived from biomass, can contribute to reducing greenhouse gas emissions compared to fossil fuels. If the study confirms its viability and environmental benefits, it could influence policymakers to promote biocoke as a cleaner alternative to traditional fossil fuels, aligning with global efforts to mitigate climate change.
b. Renewable Energy Policies.
   A positive study on biocoke could influence the development of renewable energy policies, encouraging governments to provide incentives and subsidies for the production, distribution, and use of biocoke. This could include

feed-in tariffs, tax credits, or grants to promote research and development, support infrastructure development, and attract investment in biocoke production.

c. Energy Independence and Security.
Biocoke can enhance energy independence and security for countries as a renewable and potentially locally sourced fuel. Depending on the study results, policymakers may consider prioritizing the development of domestic biocoke production and reducing reliance on imported fossil fuels.

d. Economic Opportunities.
The study's findings can influence the development of a biocoke industry, creating new economic opportunities. This could include job creation in biomass production, processing facilities, and related industries. Additionally, if biocoke proves to be a commercially viable fuel, it could stimulate investment and innovation in the renewable energy sector, attracting entrepreneurs and fostering economic growth.

e. Technological Advancements.
A study on biocoke may highlight the need for research and development to improve the efficiency, cost-effectiveness, and scalability of biocoke production processes. Governments and industry stakeholders could collaborate to support technological advancements, such as refining production techniques, optimizing biomass sourcing, and improving combustion efficiency.

f. Sustainability Considerations.
Policymakers will need to consider potential sustainability concerns associated with biocoke production. This includes ensuring that the biomass used for biocoke production is obtained from sustainable and responsibly managed sources. Environmental safeguards and standards may need to be established to prevent deforestation, protect biodiversity, and maintain soil and water quality.

g. Collaboration and Knowledge Sharing.
The study's results could prompt collaboration among researchers, policymakers, and industry experts. Knowledge-sharing platforms, conferences, and partnerships may be established to exchange best practices, share research outcomes, and promote the adoption of biocoke as a sustainable fuel option.

9. Conclusions and prospects

Utilization of bio-coke synthesis from solid biomass renewable energy sources will become very important in the future. Thus, dependence on conventional fuels for power generation can be reduced. The efficiency of agricultural waste management in energy recovery can be further increased, and GHG emissions can be minimized through a lower carbon combustion process. In addition, potential sources of bio-coke can be amended, fertilizing, capturing, and storing carbon, as well as pollutant adsorption. Agricultural biomass residues compatible with bio-coke production materials have strong properties under high pressure. In addition, adsorption capacity, high combustion characteristics, low ash, and high carbon content have also been described in this work. Carbonization, pyrolysis, assisted carbonization, and slow pyrolysis are suitable technologies for bio-coke production. The mechanical properties of bio-coke can be improved by using the carbonization method through modification because it can increase the pressure so that the required processing temperature can be reduced. Agricultural waste generated annually in Indonesia and high energy demand and consumption will increase interest in producing bio-coke. The development of future research, especially to utilize solid biomass waste of all types, is highly recommended. This can be done by modifying the bio-coke production process by introducing pre-treatments so that the utilization and feasibility of bio-coke can be further increased and slow pyrolysis is a very suitable technology for bio-coke production. The mechanical properties of bio-coke can be improved by using the carbonization method through modification because it can increase the pressure so that the required processing temperature can be reduced. 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CRediT authorship contribution statement

Asri Gani: Conceptualization, Methodology, Software. **Erdiwansyah:** Writing – original draft. **Edi Munawar:** Visualization, Investigation. **Mahidin:** Review & editing. **Rizalman Mamat:** Review & editing. **S.M. Rosdi:** Data curation, Collection data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Further reading

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