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A Review on the thermochemical conversion of sugarcane bagasse into biochar

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ABSTRACT

Sugarcane bagasse (SCB) is the fibrous lignocellulosic residue left over after crushing sugarcane to extract juice for sugar and ethanol production. In this review, a concise overview of existing thermochemical technologies for the production of biochar from SCB and its potential applications is presented and discussed. Some of the technologies used so far in this regard include pyrolysis, gasification, hydrothermal carbonization, and torrefaction. However, pyrolysis was found to be the most widely used among them. These processes can be affected by several operating conditions such as temperature, heating rate, particle size, and residence duration, with temperature being the most significant and efficient variable influencing the quality of the biochar. The yield of SCB biochar reported in the literature ranged from 14 % to 56 %. A higher yield of biochar can be obtained at a lower temperature than at a higher one because biochar decomposes at higher temperatures (>500 °C). SCB biochar has promising applications in agriculture and the environment, including soil amendment, adsorbent in water and wastewater treatment, supplementary cementitious material, amongst others. Some knowledge gaps were also stated in the study, such as the cost analysis and comparison of utilizing bagasse as fuel in sugar industries and for the production of biochar. Sugarcane bagasse biochar has the potential to become a highly promising carbon material with a wide range of applications in a variety of sectors.

1. Introduction

Biomass can be described as a renewable resource obtained from living organisms (Chen and Yan, 2020; Gonzaga Fraga et al., 2019). It can be obtained from a wide range of sources, such as agricultural crops and residues, municipal solid waste, sewage, animal residues, industrial residues, and forestry crops and residues (Firouzi et al., 2021; Zhai et al., 2021). Biomass has received tremendous research interest over the years because it allows conversion into high value-added products such as biofuel and biochar (Ogunlalu et al., 2021; Ajala et al., 2021). It is the only carbon-containing renewable fuel that favours simultaneous climate protection due to CO_2 neutrality, and as a result, there has been an increased global interest in the utilization of biomass for energy generation (Hoang et al., 2021). However, improper deposition of biomass waste in the environment has been reported to cause severe environmental degradation as it makes the environment unfit for both plants and animals (Arpia et al., 2021; Cho et al., 2020). According to the United Nations Environmental Program, about 140 billion metric tons of waste from biomass are generated across the globe in the agricultural sector alone (Martirena and Monzó, 2018). This has led several researchers, in a bid to reduce the amount of biomass waste in the environment, to convert these biomass wastes into energy and other useful materials that can be reused (Emenike et al., 2022). The increase in the production of waste and the growing need for waste management alternatives have seen the systematic conversion of biomass into biochar emerge as a low-cost solution to the problem (Emenike et al., 2022; Adeniyi et al., 2022). The application of agricultural wastes as feedstock for the production of biochar can enhance waste management practice and protect the environment (Karić et al., 2022).

Biochar can be described as a solid product containing carbon and

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mineral elements obtained from the thermochemical conversion of biomass such as combustion, gasification, hydrothermal liquefaction, torrefaction, and pyrolysis (Iwuozor, 2019; Adeniyi et al., 2022). It is obtained when biomass materials are charred/pyrolysed in an oxygen-deficient environment (Iwuozor et al., 2021; Adeniyi et al., 2022). This material has gained wide public knowledge due to its wide range of applications (Zhou et al., 2021; Adeniyi et al., 2022). It has been used in the environmental sector to lower the concentration of carbon dioxide and other atmospheric greenhouse gases (Li et al., 2018; Zhang et al., 2019), to generate renewable energy (Zhang et al., 2019; Bhatia et al., 2021), and as an adsorbent to remove pollutants from the environment (Yu et al., 2018; Boni et al., 2020; Safie and Zahrim, 2021; Iwuozor et al., 2022). It has also found application in the agricultural sector to improve soil structure and properties, including soil cation exchange capacity (Kharel et al., 2019; Gondek et al., 2019), organic content (Jing et al., 2020), soil pH (Liao and Thomas, 2019), soil aeration status (Obia et al., 2018), and water retention ability (Razzaghi et al., 2020; Wang et al., 2019). Besides the mentioned advantages and applications of biochar, it should be noted that biochar can positively affect plant growth. It can also mitigate the adverse effects of drought stress on plants. Furthermore, biochar application can affect the physiochemical properties of soils, e. g., soil structure and aggregate stability indices, soil strength, hydrophobicity of soils, adsorption–desorption of heavy metals and pollutants, fractionation of elements, and availability of nutrient elements for plants (Gavili et al., 2018; Li et al., 2021; Hardy et al., 2019; Gavili et al., 2019; Zahedifar, 2020; Zahedifar and Moosavi, 2020; Zahedifar, 2017; Zahedifar and Moosavi, 2017). Other uses for biochar include fuel cells (Ali et al., 2019; Xie et al., 2020), catalysts (Chao et al., 2020), photoactive components (Wu et al., 2020; Aggarwal et al., 2020); production of super-capacitors (Jiang, 2017; Cheng et al., 2017) and for the production of plastic composites (Adeniyi et al., 2020; Adeniyi et al., 2021; Onifade et al., 2020). The features of biochar, like pH, stability, porosity, specific surface area (SSA), cation exchange capacity, and carbon removal ability, mostly determine any biochar's performance in various applications (Li et al., 2019).

Sugarcane bagasse (SCB) is the fibrous lignocellulosic residue of sugarcane after it has been crushed for the extraction of its juice used for sugar and ethanol production (Iwuozor et al., 2021; Iwuozor et al., 2021; Iwuozor et al., 2022; Iwuozor et al., 2022; Iwuozor et al., 2022; Igwegbe et al., 2022). It is estimated that about 700 million tons of bagasse are produced annually throughout the world (Monteiro et al., 2016), corresponding to about 25–26 % of the total sugarcane production (Moretti et al., 2018; Frías et al., 2011). Bagasse is the most important by-product of sugarcane production and one of the most abundant agricultural wastes in the world (Candido et al., 2017). This waste is mostly used for the generation of electricity for cogeneration boilers in sugar production, and the surplus electricity is exported to the grid. The use of SCB as a conventional electricity distribution has been reported in even developing countries such as Cuba (Gil et al., 2013) and South Africa (Mashoko et al., 2013). However, SCB obtained from the domestic consumption of sugarcane is mostly discarded on the streets, while some ends up in refuse dumps in under-developed and developing countries. Just like other biomass, SCB is rich in carbon, cheap, highly abundant and suitable for biochar production (Iwuozor et al., 2022), and its biochar can be produced at a relatively low temperature without complex or sophisticated equipment (Creamer et al., 2014).

The abundance of this material (SCB), together with the need to minimize its presence in the environment, has motivated researchers to study the process of its thermochemical conversion to biochar. However, with the rich volume of published literature on the subject matter, there is no study that reviews the various studies performed on the thermo-conversion of SCB to SCB biochar to the best of the authors' knowledge, and this study hopes to fill that gap. This study is a review of literature discussing the thermochemical conversion of SCB into biochar. It studies the processes and operating conditions that have been used in recent times for the conversion. It also gives an overview of the characteristics of SCB biochar and their application. This study hopes to bridge the gap between studies previously performed centered on the thermochemical conversion of SCB into SCB biochar and futuristic studies in this area of research.

2. Synthesis of SCB biochar

Over the years, there have been several thermochemical methods employed for the production of biochar from sugarcane bagasse. These methods include pyrolysis (Prasannamedha et al., 2020), gasification (Enaime et al., 2020), hydrothermal carbonization (Qu et al., 2021), and torrefaction (Manatura, 2020). These methods with varying process conditions are crucial in determining the physical and chemical properties of the biochar, such as surface area, microporosity, and hydrophobicity, during the production process (Ali et al., 2019). In addition to the effect of the process conditions on the physical attributes of the resultant biochar, it also significantly affect the organo-chemical characteristics of the resultant biochar (Moradi-Choghamarani et al., 2019). Table 1 shows the different thermochemical conversion methods and their process conditions.

2.1. Pyrolysis

Pyrolysis is the thermochemical decomposition of biomass under anaerobic or anoxic conditions at temperatures between 250 and 900 °C (Mohapatra and Singh, 2021; Ighalo et al., 2022). It involves the conversion of lignocellulosic components such as lignin, cellulose, and hemicellulose (Rodier et al., 2019), into the production of valuable components such as solids (biochar), liquids (biofuels), and gases (syngas) via chemical reaction processes like depolymerisation, fragmentation, and cross-linking (Yaashikaa et al., 2020; Ighalo et al., 2021). The process involves washing, drying, grinding of biomass, pyrolysis, and separation of products (Saleh and Hedia, 2018). The biochar yield during the pyrolysis process is a determinant of the nature of the biomass used, the type of reactor, and process conditions (heating rate, residence time, pressure, and temperature) (Ighalo and Adeniyi, 2021). For example, a pyrolysis process at a higher temperature produces greater physicochemical recalcitrance in biochar than at a lower temperature. This is as a result of more carbon that is aromatic (Ali et al., 2019). Depending on the process conditions (heating rate and residence time), pyrolysis is classified into slow pyrolysis and fast pyrolysis (Stegen and Kaparaju, 2020).

2.1.1. Slow pyrolysis

Slow pyrolysis process involves heating the biomass at a rate less than 5 – 10 °C/min and a long residence time greater than 30 mins (Varma and Mondal, 2016). The process is usually optimized to yield

Table 1
Thermochemical conversion methods and their process conditions.

Methods	Temperature (°C)	Residence time	Biochar yield (%)	Ref.
Pyrolysis	400–550 (slow) 400–800 (fast)	40 mins (slow)Hour-day (fast)	31–34 (slow)47 (fast)	(Quirk et al., 2012) (Sohaib et al., 2017)
Hydrothermal carbonization	180–230	13 – 40 h	78	(Vitor et al., 2021)
Gasification	700 – 900	10 – 30 mins	10 – 13	(Raheem et al., 2019)
Torrefaction	160 – 300	2 h	55–95	(Valix et al., 2016)

biochar as the main product, but it is often accompanied by liquid and gaseous products (Quirk et al., 2012). A recent study by Ali et al. (Ali et al., 2019) identified the most environmentally relevant physico-hydraulic characteristics of slow-pyrolysis sugarcane-derived biochar at varying temperatures. The results showed that the average pore diameter of the biochars decreased with increasing pyrolysis temperature and the adsorptive behaviour of the biochar increased with rising pyrolysis temperature.

2.1.2. Fast pyrolysis

Fast pyrolysis process involves a moderate temperature, a higher heating rate of about 10–200 °C, and a shorter residence time, usually less than 10 s (Varma and Mondal, 2016). This process produces more bio-oil (Stegen and Kaparaju, 2020). Sohaib et al. (Sohaib et al., 2017) investigated the effects of fast pyrolysis conditions by subjecting sugarcane bagasse to a bench scale reactor. The results showed the relationship between an increase or decrease in biochar yield with bagasse size and temperature.

Pyrolysis processes have greatly improved in order to increase the yield of biochar. For example, Paramasivan (Paramasivan, 2021) evaluated the influential factors in microwave-assisted pyrolysis of sugarcane bagasse from biochar production and Mohapatra and Singh (Mohapatra and Singh, 2021) explored the co-pyrolysis of sugarcane bagasse and thermocool waste in a semi-batch reactor.

2.2. Hydrothermal carbonization

Hydrothermal carbonization (HTC), which is also known as wet pyrolysis, is a thermochemical decomposition of biomass to produce a carbon-rich material, known as hydrochar, and a liquid fraction, known as process water, at a medium temperature, usually between 180 and 350 °C and an autogenous saturated vapour condition (10–80 bars) (Bisinoti et al., 2020; Kim et al., 2020; Ighalo et al., 2022). The process, which is affected by different conditions such as reaction time, temperature, the proportion of biomass, and aqueous phase, is a spontaneous and exothermic process that involves blending the biomass (sugarcane bagasse) with water and feeding it into a closed reactor (Vitor et al., 2021). This process is cost-effective because it can be performed at a low temperature and does not include drying operations (Sharma et al., 2019). However, some of the limitations of preparing hydrochar from the hydrothermal carbonization process include the low surface area and lower porosity of hydrochar (Zhou et al., 2022:). Several studies have been conducted on the hydrothermal carbonization of sugarcane bagasse for biochar production. For example, the research by Prasannamedha et al. (Prasannamedha et al., 2020) focused on the production of biochar from sugarcane bagasse through HTC, followed by NaOH activation for the removal of sulfamethoxazole (SMX) in water. The result showed that HTC derived biochar had a great adsorption affinity for SMX and can serve as an effective sorbent for contaminants' removal. Qu et al. (Qu et al., 2021) explored the use of in situ sulphuric acid-modified biochar derived from the hydrothermal carbonization of sugarcane bagasse for the adsorption–desorption of toluene. The result showed an excellent toluene adsorption capacity (771.1 mg/g) at 30 °C.

2.3. Gasification

Gasification is a thermochemical method of decomposing sugarcane bagasse biomass or other organic matter into gaseous products (syngas) containing H_2, CO, CO_2, CH_4, traces of hydrocarbons, a solid char (biochar), and liquid product (tar) at high temperatures, typically between 700 and 1000 °C (Aburto, 2021; Centeal). The process involves five discrete sub-processes: pyrolysis, combustion, cracking, and reduction. The main product is the syngas, while the char and tar are the undesirable by-products. The char properties produced from biomass gasification are a determinant of reactor design, gasifying agent, and gasifying temperature. It is observed that the reaction temperature is the most significant factor in syngas production (Raheem et al., 2019).

2.4. Torrefaction

Torrefaction is a thermochemical pretreatment for the conversion of biomass to “charred” products, thereby reducing the cost of transportation, handling, downstream processing, and storage and improving characteristics such as hydrophobicity or water-resistivity, energy density, grindability and reactivity, biomass brittleness, lower atomic O/C and H/C ratios, and uniformity (Granados et al., 2017). Generally, it is a mild pyrolysis pretreatment of biomass in an inert reactor at a temperature between 200 and 300 °C with low heating rates, usually within 0.5–3 hrs. (Arpia et al., 2021). This process, which is typically considered a more cost-effective and environmentally friendly technology than gasification and pyrolysis due to its energy requirements, involves the heating of sugarcane bagasse within an engineered reactor where heat is added from an external fuel source that is directly or indirectly applied to the sugarcane bagasse undergoing conversion into a “torrefied bagasse” (Barskov et al., 2019). The torrefaction of sugarcane bagasse has been widely studied and advocated for in literature. For example, Manatura (Manatura, 2020) examined the torrefaction performance and characteristics of sugarcane bagasse in an inert environment. The results showed that temperature affected the chemical and physical properties, while duration time was insignificant. Valix et al. (Valix et al., 2016) carried out the torrefaction of sugarcane bagasse with an acid in a nitrogen environment at temperatures ranging from 160 to 300 °C. They reported that the thermochemical torrefaction process generated chars with combustion properties similar to various ranks of coal, addressing the practical challenges of using biomass such as bagasse as fuel. Kanwal et al. (Kanwal et al., 2019) studied the effect of torrefaction conditions (temperature and residence time) on the physicochemical characterization of sugarcane bagasse. Results indicated that an increase in temperature and residence time is significant for improving the characteristics of torrefied bagasse.

3. Effect of operating conditions on SCB biochar production.

Thermochemical processes such as pyrolysis, liquefaction, carbonisation, and torrefaction can yield biochar from SCB processing. In this section, we discuss the effects of various operating conditions on the yield of biochar from SCB.

3.1. Temperature

Temperature is the most important factor that affects the yield of SCB biochar. This is because SCB biochar is produced from a thermal process that requires the high-temperature breakdown of the parent biomass constituent. We will discuss the temperature effects for various process types for SCB biochar production (summarised in Table 2). As observed by Ding et al. (Ding et al., 2014) and Hafshejani et al. (Hafshejani et al., 2016), maximum biochar yield was achieved at the lower temperature interval for the pyrolysis process. This suggests that lower temperatures below 300 °C favour SCB biochar yield compared to higher temperatures. This could be because high temperatures favour the formation of non-condensable gases which in turn lowers the biochar's yield. Pyrolysis is essentially the thermal breakdown of materials under inert conditions (Luo et al., 2015). Hence, a greater intensity of thermal breakdown at a higher temperature will likely result in lighter chemical species in the product than would exist in the liquid or gaseous phases (Guida and Hannioui, 2017). Sometimes, pyrolysis can be achieved by microwave heating (Paramasivan, 2021). Lin and Chen (Lin and Chen, 2015) have shown that microwave pyrolysis will lead to more biochar yield compared to conventional heating under similar process conditions (albeit for SCB).

Thermal liquefaction using solvents and SCB can also yield biochar (Araújo et al., 2021). For SCB, solvents such as anhydrous ethanol and

Table 2
Summary of optimum temperature and yield for SCB biochar production.

Process	Temp interval (°C)	Optimum Temp (°C)	Biochar yield (wt %)	Ref.
Pyrolysis	250 – 600	250	77.1	(Ding et al., 2014)
Pyrolysis	200 – 600	200	29.3	(Hafshejani et al., 2016)
Thermal liquefaction (using fuse oil solvent)	–	300	21.0	(Araújo et al., 2021)
Thermal liquefaction (using ethanol solvent)	–	300	28.0	(Araújo et al., 2021)
Pyrolysis	300 – 800	300	39.7	(Guida and Hannioui, 2017)
Pyrolysis	400 – 800	400	38.0	(Kameyama et al., 2019)
Pyrolysis	450 – 550	450	25.9	(Lin and Chen, 2015)
Pyrolysis	350 – 600	350	36.0	(Saif et al., 2020)
Microwave pyrolysis	–	500	47.35	(Debalina et al., 2017)
Microwave pyrolysis	–	550	61.9	(Lin and Chen, 2015)
Retort carbonisation	25 – 349	349	16.67	(Adeniyi et al., 2021)
Pyrolysis	300 – 600	300	53.54	(Stegen and Kaparaju, 2020)
Pyrolysis	350 – 650	350	49.45	(Varma and Mondal, 2017)

fuse oil have been reported (Araújo et al., 2021). Usually, biochar is a residue from the process, and the major product of interest is the generated liquid. Though the temperature effect was not directly studied, Araújo et al. (Araújo et al., 2021) observed variations in residual biochar yields for the different solvents at similar temperatures. Retort carbonisation is a self-regulating process where the combustible off-gases from the controlled combustion of biomass are re-combusted for the conversion of the SCB to biochar (Ighalo et al., 2022). Hence, there are no temperature controls and the system heats up to a peak temperature from ambient conditions and falls back to ambient conditions again. The peak temperature is determined by the heating values of the combusted biomass and the design of the reactor. Adeniyi et al. (Adeniyi et al., 2021) observed an SCB biochar yield of 16.67 wt% at a peak temperature of 349 °C.

3.2. Heating rate

The heating rate has also been observed to play an important part in the yield of biochar from SCB under various processes. Guida and Hannioui (Guida and Hannioui, 2017) explained that for SCB pyrolysis, the yield of biochar can be significantly decreased at a rapid heating rate. Lesser biochar is produced from the primary reactions because there is fast depolymerisation of the SCB. Similar observations have been made by Varma and Mondal (Varma and Mondal, 2017) for SCB pyrolysis. Torrefaction tends to give a lower biochar yield because the operating temperature tends to be lower and the biomass thermal disintegration is only partial. Chen et al. (Chen et al., 2017) achieved 85.6 wt% biochar yield at an optimum heating rate of 10.6 °C/min. Athira et al. (Athira et al., 2021) observed that the yield of biochar increased from 1.44 wt% at a heating rate of 10 °C/min to a peak of 6.97 wt% at 50 °C/min. The lesser yield at the lower heating rate was attributed to the longer exposure time experienced by the SCB samples at lower heating rates. A summary of the heating rate effect on SCB biochar yield as reported in the literature is summarised in Table 3.

3.3. Other factors

Other parameters have been observed to affect the yield of biochar from SCB thermochemical processing. The size of the SCB particles used for the processing techniques has also been shown to affect the biochar yield. In the case of pyrolysis, Saif et al. (Saif et al., 2020) observed that the yield of biochar increases with an increase in the particle size of the SCB used. It was proposed that larger particle sizes result in a significant temperature gradient (a wide difference between core and outer temperature), signifying less efficiency in internal heat transport, thereby leading to more biochar production as opposed to liquid products. Similar observations on the effect of particle size on SCB pyrolysis have been made by Sohaib et al. (Sohaib et al., 2017) and Varma and Mondal (Varma and Mondal, 2017).

The residence time is the time the SCB spends in the reactor before elutriation. It is quite different from the heating rate (though they affect each other). Essentially, longer residence time will lead to more secondary pyrolysis reactions, thereby increasing the extent of thermal breakdown (Miranda et al., 2021). Based on this, it is evident that longer residence time will lead to lesser SCB biochar in theory. However, in practice, slow pyrolysis with longer residence time produces more biochar. This is because, in this case, the effect of the slow heating rate is more significant than the residence time itself.

In pyrolysis investigations where N_2 is required to create an inert environment, the flow rate of the gas becomes an important factor. At higher N_2 flow rates, it has been observed that the yield of biochar decreased (Saif et al., 2020). Besides the creation of an inert environment, the gas flow reduces the residence time of the product vapour, thereby reducing secondary reactions and re-polymerisation. Similar observations have been made on the effect of N_2 flow rates on SCB biochar yield by Varma and Mondal (Varma and Mondal, 2017).

4. Yield and proximate characteristics of SCB biochar

Table 4 shows the yield and proximate analysis of some reported SCB biochar. The production temperature and the nature of the feedstock are the major factors that determine the quantitative and qualitative yield of biochar, as well as the product composition (Guida and Hannioui, 2017; Zhao et al., 2017). Indeed, temperature affects the properties of biochar even more than the heating rate and residence time (Zhao et al., 2018). As can be observed from Table 4, a higher biochar yield is attainable at a low temperature than at a high temperature for the lignocellulosic material. This is probably because biochar decomposes at temperatures above 500 °C (Behera et al., 2020). Ahmed et al. (Ahmed et al., 2021) reported a decrease in biochar yield from 30.10 to 14.67 wt% as the

Table 3
Summary of heating rate and yield for SCB biochar production.

Process	Temp interval (°C)	Rate interval (°C/min)	Optimum rate (°C/ min)	Biochar yield (wt %)	Ref.
Pyrolysis	400–700	10 – 50	50	6.97	(Athira et al., 2021)
Torrefaction	200–300	4.4 – 10.6	10.6	85.6	(Chen et al., 2017)
Pyrolysis	300–800	5 – 50	5	39.7	(Guida and Hannioui, 2017)
Pyrolysis	350–650	10 – 50	10	49.45	(Varma and Mondal, 2017)

Table 4
Some reported SCB biochar properties.

Process	Production Temp. (°C)	BET surface area (m^2/g)	Biochar yield (%)	Proximate analysis (wt%)				Ref.
				Volatile matter	Moisture content	Ash content	Fixed carbon	
Retort carbonization	349	533.6	16.67		–	–	–	(Adeniyi et al., 2021)
Pyrolysis	1000	–	14.67	13.7	17.0	5.67	62.8	(Ahmed et al., 2021)
Pyrolysis	400	–	30.10	40.0	3.69	4.05	52.2	(Ahmed et al., 2021)
Pyrolysis	600	–	18.30	43.2	1.60	6.15	49.1	(Behera et al., 2020)
Pyrolysis	300	–	56.27	68.5	3.00	3.62	24.9	(Behera et al., 2020)
Pyrolysis	750	–	26.90	7.70	–	2.20	90.1	(Domingues et al., 2017)
Pyrolysis	700	98.47	25.34	10.2	2.38	9.47	77.9	(Jia et al., 2020)
Pyrolysis	400	27.49	37.38	14.7	2.59	4.26	78.5	(Jia et al., 2020)
Pyrolysis	500	148.2	25.00	–	5.70	4.70	74.9	(Vimal et al., 2019)
Pyrolysis	700	131.0	–	17.2	–	12.5	70.3	(Trazzi et al., 2016)
Pyrolysis	300	4.930	–	46.9	–	3.44	49.7	(Trazzi et al., 2016)

pyrolysis temperature increased from 400 to 1000 °C. Similarly, Behera et al. (Behera et al., 2020) observed that the yield of SCB biochar sharply decreased from 56.27 wt% at 300 °C to 18.30 wt% at 600 °C.

The composition of the biomass also affects its biochar yield, particularly the lignin content and inorganic constituents such as ash and fixed carbon (Cheng and Li, 2018). Biomass with high lignin content, such as sugarcane bagasse, tends to produce a higher biochar yield (Behera et al., 2020). Other factors that may likely influence the yield of the biochar include the biomass growing conditions, age, geographical location, and method and season of harvest. Hass and Lima (Hass and Lima, 2018) observed that lots of differences exist between the properties of biochar obtained from old sugarcane bagasse and that from fresh sugarcane bagasse. The biochar from the former has a higher yield (37 + 2.0 %) than the latter (27 + 2.0 %), and demonstrated higher metal sorption capacity. In addition, inorganic elements such as alkaline and alkaline earth metals present in the biomass can act as catalysts during pyrolysis, thus increasing the biochar yield (Zhao et al., 2017).

A biochar proximate analysis includes the volatile matter, moisture, ash, and fixed carbon content. Ash content is a measure of the non-volatile and non-combustible components (Jia et al., 2020). From Table 4, it can be observed that the ash and fixed carbon contents of SCB biochar tend to increase as the production temperature increases. This is a common trend with most biomass-derived biochar (Hass and Lima, 2018). High fixed carbon content is also a property of lignin-rich biomass-derived biochar (Behera et al., 2020). Biochar ash content is rich in alkaline nutrients and can be used in neutralising soil acidity (Domingues et al., 2017). Aside from the proximate analysis, SCB biochar, like other biochars, is commonly characterized by the presence of several inorganic elements (ultimate analysis), such as carbon, hydrogen, nitrogen, oxygen, and sulphur. It has been reported that nitrogen is always low in biochar obtained from high lignin-containing biomass (Jia et al., 2020). The inorganic compounds, which are inherent properties of the biomass, facilitate the yield of biochar and gaseous species at the expense of bio-oils during the production process (Hass and Lima, 2018). Hence, the presence of some of these minerals is directly linked to high biochar yield. There is also the presence of hydrocarbons and organic carbon in SCB biochar. Higher values of hydrocarbons and organic carbons indicate a relatively high content of aliphatic and oxidized substances, while lower values suggest a relatively higher content of aromatic and reduced substances (Hass and Lima, 2018). SCB biochar with high aliphatic carbon content and low aromatic carbon content is less appealing as a carbon sequestering agent because it degrades quickly in soil (Uras et al., 2012). Table 4 also includes the BET surface areas of the biochars. The surface area represents the physical development that occurs during the thermochemical conversion of biomass to biochar and is connected to the sorption ability of biochar (Uras et al., 2012).

5. Applications of SCB biochar

SCB biochar has found application in many fields, particularly in agriculture and water treatment. Some of the areas are discussed in this section.

5.1. Soil amendment

Agriculture is probably the sector that utilizes biochar the most. Biochar has continued to receive attention as an important tool for soil carbon abatement while simultaneously adding several benefits to soil fertility (Cross and Sohi, 2013). SCB biochar is used in agriculture for several purposes, including application as a fertilizer to improve soil nutrients and increase crop yield, stabilize heavy metals in the soil, reduce N_2O emissions, and sequester carbon.

SCB biochar can be used as a fertilizer because it has the potential to provide phosphorus and potassium, as well as supplement the soil organic carbon (Amin, 2020). As a fertilizer, biochar, unlike inorganic fertilizers, can interact with the contaminants in the soil using its non-carbonized fraction to improve soil properties (Fang et al., 2020). Also, owing to its high carbon content, biochar can stimulate and maintain soil organic matter, aggregation, nutrients, porosity, and water holding capacity in non-saline soils (Azadi and Raiesi, 2021). Amin (Amin, 2020) used SCB biochar to improve the nutrients of calcareous sandy soil. The addition of the biochar significantly improved the availability of phosphorus and potassium in the soil and enhanced carbon sequestration, which in turn plays a crucial role in the mitigation of climate change. In another study carried out in an arid zone agricultural field, Azeem et al. (Azeem et al., 2019) found that application of SCB biochar to the soil improved soil organic matter, total nitrogen, and crop yield and decreased soil bulk density. This result suggests the use of SCB biochar in soil amendments could enhance crop yield and lower global warming potential.

SCB Biochar is also used in the stabilization of heavy metals in the soil (Zahedifar, 2020; Zahedifar and Moosavi, 2020; Zahedifar, 2017; Zahedifar and Moosavi, 2017). Stabilization is a remediation technique whereby non-toxic substances are used to minimize the solubility of heavy metal contaminants in soil, hence reducing their leachability into the ground water and the environment (Abdelhafez et al., 2014; Chen et al., 2006). Abdelhafez et al. (Abdelhafez et al., 2014) investigated the effects of SCB biochar on the physical and chemical properties of a metal smelter-contaminated soil. It was discovered that the introduction of biochar significantly increased the soil aggregate stability, water-holding capacity of the soil, soil exchange capacity, organic matter and nitrogen content of the soil. Also, the addition of the biochar decreased the solubility of the heavy metal, Pb, to levels acceptable for leaching of toxic metals. Similar results were also reported by Haghighatjou and Shirvani (Haghighatjou and Shirvani, 2020) and

Zahedifar (Zahedifar, 2020).

Agricultural activities such as cattle grazing, deposition of manure, and fertilizer application are major contributors to greenhouse gas effects, as they emit an enormous amount of nitrous oxide (N_2O) into the soil (Domingues et al., 2017). This emission can be minimized by treating the contaminated soil with biomass-derived biochar, such as SCB biochar. The rate of N_2O emissions reduction by biochar-treated soils can be influenced by various factors, including the type of biochar feedstock, production method and temperature, biochar yield and soil properties. The rate of N_2O emissions reduction by biochar-treated soils can be influenced by various factors, including the type of biochar feedstock, production method and temperature, biochar yield, and soil properties (Domingues et al., 2017). Biochars pyrolysed at temperatures above 400 °C have been recommended for the reduction of N_2O emissions from soil (Cayuela et al., 2014).

5.2. Adsorbent for water treatment

Biomass-derived biochar has been widely used in recent times for the removal of heavy metals and other water pollutants because of its low-cost, abundance, and excellent surface properties (Adeniyi et al., 2019; Iwuozor et al., 2021; Iwuozor et al., 2022; Emenike et al., 2022; Zhulquarnain et al., 2018). Adsorption using several adsorbents, such as biochar, is considered one of the most effective means of removing various contaminants from aqueous solutions (Emenike et al., 2021; Iwuozor et al., 2021; Ogunlalu et al., 2021; Iwuozor et al., 2021; Ighalo et al., 2022). Biochar has unique surface properties such as polar and hydrophilic nature, a porous structure, and relatively high surface area-to-weight ratios, making it a promising adsorbent for even gaseous pollutants (Creamer et al., 2014; Hafshejani et al., 2016; Adeniyi et al., 2020). Despite having less surface area and porosity than activated carbon, biochar has more acid functional groups, such as oxygenated functional groups (hydroxyl, phenolic, and carboxylic groups), which facilitate metal adsorption (Doumer et al., 2016; Rangabhashiyam et al., 2022). Hence, biochar has been reported to uptake metal ion pollutants more efficiently than commercial activated carbon (Tong et al., 2011; Cao et al., 2011). The sorption of metal ions onto the surface of biochar is mostly through cation exchange, followed by complexation between oxygenated functional groups and metal ions (Ding et al., 2014; Doumer et al., 2016). Although in the presence of anions released by the biomass, such as phosphate and hydroxide, metal precipitation may also occur (Doumer et al., 2016). In addition, biochar does not need to be recycled after the adsorption process, as the spent biochar can be further used as fertilizer to improve soil fertility and sequester carbon (Hafshejani et al., 2016; Adeniyi et al., 2022).

Modification of the biochar can increase its surface properties and enhance the adsorption process (Liu et al., 2022). In the uptake of nitrate using raw and chemically-modified SCB biochar investigated by Hafshejani et al. (Hafshejani et al., 2016), the maximum sorption capacity was found to increase from 11.56 mg/g with the raw biochar to 28.21 mg/g with the modified biochar. The production temperature also plays an important role in the sorption of pollutants by the SCB biochar. Ding et al. (Ding et al., 2014) reported the high influence of pyrolytic temperature on the sorption of Pb by SCB biochar. As the pyrolytic temperature increased from 250 to 600 °C, the maximum sorption capacity decreased from 21 to 6.1 mg/g. The higher sorption onto low temperature biochar was attributed to the presence of oxygenated functional groups, whereas intraparticle diffusion was responsible for the low sorption capacity onto high temperature biochar (Ding et al., 2014). Table 5 presents some of the reported sorption capacities of SCB biochar in the removal of various pollutants from the aqueous environment.

Table 5
Maximum sorption capacity of SCB biochar in the removal of pollutants.

Adsorbent	Adsorbate	pH	Temp. (°C)	Maximum sorption capacity (mg/g)	Ref.
Zn-modified SCB biochar	Cr^{6+}	2.0	–	102.7	(Gan et al., 2015)
SCB biochar	CO_2	–	25	73.55	(Creamer et al., 2014)
SCB biochar	Methylene blue	10	25	113.0	(Biswas et al., 2020)
SCB biochar	NO_3	3.0	22	11.56	(Hafshejani et al., 2016)
Chemically-modified SCB biochar	NO_3	3.0	22	28.21	(Hafshejani et al., 2016)
SCB biochar	Pb^{2+}	–	–	21.00	(Ding et al., 2014)
SCB biochar/Fe_2O_3/Fe_3O_4	Cr^{6+}	2.0	25	55.00	(Bai et al., 2021)
SCB biochar	Chlortetracycline	4.0	25	16.96	(Zhang et al., 2018)
SCB biochar	Carbofuran	6.0	45	18.90	(Vimal et al., 2019)

5.3. Supplementary cementitious material

The cement industry is responsible for approximately 1.8 GT of all CO_2 emissions globally, as well as 5–7 % of total anthropogenic CO_2 emissions (Zeidabadi et al., 2018; Gao et al., 2015). This is because ordinary Portland Cement (OPC), which is the major cementing agent, emits a lot of CO_2 and is often associated with environmental degradation (Ighalo and Adeniyi, 2020). Agricultural waste biochar can be used as a cementitious or pozzolanic material to partially replace OPC in cement production without any side effects on the final product or the environment (Meko et al., 2021). This process allows the biochar concrete to sequester carbon instead of releasing the CO_2 and methane associated with its disposal (Zeidabadi et al., 2018). Zeidabadi et al. (Zeidabadi et al., 2018) replaced OPC with 5 % SCB biochar in concrete production and found that the comprehensive strength of the substituted sample increased by 24.4 % when compared with the control concrete. There was a significant increase in the tensile strength of the biochar-substituted sample, thus showing the potential of the biochar as a candidate for green concrete production.

6. Conclusion and future perspectives

This study is a review of various published studies on the synthesis, properties, and applications of sugarcane bagasse (SCB) biochar. Some interesting observations were derived from this review. SCB biochar has been synthesized with the aid of thermochemical processes such as pyrolysis, torrefaction, hydrothermal carbonization, and gasification. Of these, pyrolysis is the most commonly used technique for the production of SCB biochar. The effects of various operating variables, such as temperature, heating rate, SCB particle size, residence time, and gas flow rate, were also studied. Temperature (which ranged from 300 °C to 1000 °C) was observed to be the most effective and significant factor affecting the property of the biochar of all the operating conditions affecting SCB synthesis, with a higher temperature of synthesis above 300 °C leading to a biochar yield of ≤50 % for most studies. This is because high temperatures favour the formation of non-condensable gases from the surface of the biochar. The properties of SCB biochar were also discussed. Sugarcane bagasse biochar has been utilised for soil amendment, as an adsorbent for water and wastewater treatment, and as a cementitious material.

Sugarcane bagasse biochar has the potential to become a highly potential carbon material with a wide range of usage for various industries. Due to the high temperature required for the conversion of bagasse into biochar, the use of non-electrically powered reactors (such as reactors powered by other biomass) for the conversion process is encouraged. Most of the studies in literature did not report the yield of SCB biochar obtained, and most of the studies that did reported a biochar yield below 30 %. Researchers are encouraged to calculate and state the yield of the SCB biochar yield obtained and also explore new technologies centred on biochar yield increase. In addition, research centered on the effect of temperature and other parameters such as the amount of oxygen in the system, on the properties and application of SCB biochar should be encouraged.

The production of electro-modified SCB biochar, which involves the impregnation of SCB biochar with chemicals and then subsequently applying electric current into the solution, should be encouraged. This method of modification has proven to be more effective in the application of biochar as an adsorbent as well as for soil amendment. In addition, the production of magnetic SCB biochar for environmental remediation treatment should be encouraged. The use of SCB biochar filters as a replacement for carbon filters for water treatment as well as activated carbon for raw sugar purification in the sugar industry has not yet been studied. Such studies, which could also involve a cost analysis, have the potential to present SCB biochar to various industries as an efficient and cost-effective carbon material. From the authors' extensive search, there is no published paper that studied the techno-economic analysis of SCB biochar. The study of the cost process would be very beneficial if compared with the cost of bagasse for electricity generation. This would help the sugar and allied industries in making cost-effective decisions (Ighalo et al., 2022).

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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