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Life-cycle assessment of pyrolysis processes for sustainable production of biochar from agro-residues

Xiefei Zhu [a,b] , Claudia Labianca [b], Mingjing He [b], Zejun Luo [a], Chunfei Wu [c], Siming You [d], Daniel C.W. Tsang [b,e*]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, 96 Jinzhai Road, Hefei, Anhui 230026, China

[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

[c] School of Chemistry and Chemical Engineering, Queen's University Belfast, David Keir Building, Stranmillis Road, Belfast BT9 5AG, UK

[d] James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK

[e] Research Institute for Future Food, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

[*] Corresponding author: dan.tsang@polyu.edu.hk

Abstract

Net carbon management of agro-residues has been an important pathway for reducing the environmental burdens of agricultural production. Converting agro-residues into biochar through pyrolysis is a prominent management strategy for achieving carbon neutrality in a circular economy, meeting both environmental and social concerns. Based on the latest studies, this study critically analyzes the life cycle assessment (LCA) of biochar production from different agro-residues and compares typical technologies for biochar production. Although a direct comparison of results is not always feasible due to different functional units and system boundaries, the net carbon sequestration potential of biochar technology is remarkably promising. By pyrolyzing agro-residues, biochar can be effectively produced and customized as: (i) alternative energy source, (ii) soil amendment, and (iii) activated carbon substitution. The combination of life cycle assessment and circular economy modelling is encouraged to achieve greener and sustainable biochar production.

Keywords: Circular economy; Renewable energy; Engineered biochar; Activated carbon; Sustainable waste management; Carbon neutrality.

1. Introduction

To meet the global target set by the Intergovernmental Panel on Climate Change (IPCC, 2018), effective reduction in greenhouse gas (GHG) emissions is required for the net-zero emissions target. Biomass utilization is one of the readily available solutions. For example, agro-residues are regarded as renewable biomass that accompanies crop harvesting and CO_2 removal during plant growth (Kapoor et al., 2020; Wang et al., 2019). However, in many regions, agro-residues are directly abandoned in the field and/or burned to release CO_2 into the atmosphere, leading to widespread environmental problems such as the emissions of smog and particulate matter (Tagade et al., 2021). Untapped opportunities for advanced and environmentally friendly management strategies of agro-residues would close the resource loop for net-zero carbon emissions and realize sustainable resource management of the agroecosystems.

As one of the most promising technologies for biomass conversion, pyrolysis can achieve co-generation of renewable energy and value-added materials (Zhu et al., 2022). Diverse types of pyrolysis technologies can be adapted to satisfy various application requirements, depending on the feedstock types, regions, and scales (Chang et al., 2018; Yuan et al., 2022). Pyrolysis can be generally classified into: (i) fast pyrolysis, (ii) intermediate pyrolysis, and (iii) slow pyrolysis, according to different heating rates and residence time, which are featured by different fractions of main products (e.g., syngas, bio-oil, and biochar) (Chantanumat et al., 2022; Yang et al., 2019). Adjustment of the pyrolysis temperature, duration, catalytic additives, and modification methods (physical and chemical activation) can further improve its product distribution and properties (He et al., 2021b; Zhu et al., 2019a).

Biochar, as a carbon-rich solid material, has a variety of application scenarios, such as soil amendment (He et al., 2021a), energy substitution (Kant Bhatia et al., 2021), adsorbents (Luo et al., 2018), catalyst supports (Yu et al., 2019), and CO_2 adsorption (Qiao & Wu, 2022), etc. Among them, biochar application for soil amendment is popular because biochar could not only improve overall soil health, such as enhanced fertility, pollution abatement, and enriched biotic population, but also contribute to carbon sequestration and climate change mitigation (He et al., 2021b). Although biochar may degrade to a certain extent under varying field conditions, its long-term carbon storage is globally recognized and beyond doubt (Li et al., 2022). In addition, biochar is a good energy carrier with a high heating value (HHV) of 12−30 MJ/kg, showing a great energy potential as a solid fuel (Zhu et al., 2018a). Therefore, biochar technology can facilitate utilization of renewable energy and valorization of agro-residues.

Nevertheless, improper selection of feedstocks and process conditions may lower the energy efficiency. For instance, when the pyrolysis temperature increased from 650 to 950 °C, the HHV for biochar showed little change yet lower yield and higher energy consumption were associated with higher temperatures (He et al., 2021b). It is recognized that larger-scale biochar production has a higher energy efficiency and a lower carbon footprint (Yang et al., 2021b). Compared to purpose-grown feedstocks, biochar derived from waste streams involved a notably lower carbon footprint (Matuštík et al., 2020).

It is important that biochar applications should clearly demonstrate environmental and economic benefits before commercialization and large-scale adoption (Tiegam et al., 2021; He et al., 2022). In recent years, life cycle assessment (LCA) of large-scale production of biochar has gradually become a hotspot. LCA is a well established and structured approach that can be used to quantify the environmental impacts of biochar production systems, providing a standardized tool to compare different feedstock types and biochar production technologies (Yang et al., 2020). LCA can also serve as a decision making tool to help policymakers and practitioners to optimize the biochar production systems. For example, LCA of biochar production systems has been investigated to understand the environmental impacts in terms of crop production, harvesting, collection, transportation, pretreatment, pyrolysis technology, and biochar application (Yang et al., 2021a). Therefore, LCA of biochar production systems is important for minimizing detrimental environmental impacts and bringing more prominent economic benefits. However, the detailed definitions of LCA, such as functional units and system boundaries, often differ across various studies, rendering cross-study comparison difficult.

Therefore, this article presents a comprehensive review of the research status and hotspots of biochar production systems from agro-residues through the LCA methodology. Accordingly, this review highlights and analyzes the key factors influencing the LCA results, which will be conducive to further enhancing the environmental and economic benefits of agro-residues management in future studies.

2. Thermochemical conversion of Agro-residues

2.1 Agro-residues category

Agro-residues are by-products of crop harvest and processing, which have great potential in terms of energy and materials application. In general, agro-residues can be divided into primary and secondary materials (Tagade et al., 2021). Primary agro-residues are the field wastes directly generated during crop harvest, such as cotton straw, wheat straw, rice straw, palm oil fronds, bunches, etc. Secondary agro-residues are from crop processing, mainly rice husks, peanut shells, walnut shells, maise cob, palm kernel shells, empty fruit bunch, palm mesocarp fiber, etc.

The properties of typical agro-residues reported in recent studies are listed in Table 1. The volatile matter of agro-residues ranges from 60.5% to 83.9% and the ash content ranges from 1.3% to 13.6%. The proportions of carbon and oxygen in agro-residues are relatively high, i.e., 35.4−61.1% and 29.8−53%, respectively. The hydrogen content is 3.1−10.6%, and the nitrogen content is usually below 3%. The properties of agro-residues play an important role in the selection of conversion routes. For example, low-moisture (<10%) agro-residues are suitable for thermochemical conversion, while the high-moisture ones are more adequate for hydrothermal carbonization or liquefaction and anaerobic digestion to reduce energy consumption associated with feedstock drying (Ma et al., 2020). Furthermore, the HHV of different agro-residues is often between 15.4 and 21.1 MJ/kg. The higher HHV is, the better the energy potential, which can be used to produce renewable energy via thermochemical conversion. It is worth noting that the same agro-residues from different places display different properties due to different soils and tillage conditions (Skinner et al., 2020).

2.2 Pyrolysis technology

The typical conversion technologies of agro-residues include combustion, pyrolysis, gasification, hydrothermal carbonization, hydrothermal liquefaction, and anaerobic digestion (Alhazmi & Loy, 2021; Zhou et al., 2016), as shown in Fig. 1. Among them, pyrolysis has notable advantages such as easy implementation and minimal water pollution. The biochar produced from agro-residue pyrolysis has proved effective for carbon sequestration, energy provision, and soil remediation. It is noted that the biochar properties are closely dependent on the pretreatment methods and the pyrolysis technology and conditions (Sun et al., 2022b).

2.2.1 Thermal pretreatment

Moisture content can significantly vary depending on the types of agro-residue. For example, primary agro-residues have higher moisture during harvest. To reduce moisture and improve utilization efficiency, drying and torrefaction are commonly adopted thermal pretreatment methods (Ma et al., 2019). Drying is carried out at low temperatures (below 200 °C), while torrefaction is conducted at 200−300 °C in a limited oxygen atmosphere (Chen et al., 2020). Based on the thermal degradation properties of the biomass components, torrefaction can be divided into light torrefaction (200−235 °C), mild torrefaction (235−270 °C), and severe torrefaction (270−300 °C) (Zhu et al., 2019c). Afterwards, torrefied agro-residues have higher carbon content, lower oxygen content, higher energy density, and increased hydrophobicity, which are beneficial for subsequent transportation, storage, and large-scale pyrolysis applications. However, drying and torrefaction involve significant energy consumption. Rational optimization of the pretreatment method, pyrolysis equipment, mass/heat transfer, temperature, and residence time would reduce the overall energy demand of the entire upgrading process.

2.2.2 Pyrolysis

Pyrolysis is a thermal degradation process at 300 °C and above in an inert atmosphere, which can convert biomass into biochar, bio-oil, and syngas (Thu et al., 2021). Slow pyrolysis employs a low heating rate (less than 10 °C/s) and a long residence time (several hours to days), and the main product is biochar. In fast pyrolysis, a high heating rate (higher than 10^3 °C/s) and a short residence time (less than 2 s) with rapid quenching of the volatiles lead to the main product as bio-oil, and biochar is a co-product (Zhao et al., 2020). Appropriate process conditions can reduce secondary reactions during pyrolysis to improve the bio-oil yield. In addition, catalysts and microwave assistance are often applied in biomass thermal conversion to improve the product distribution and quality (Lu et al., 2021; Zulkornain et al., 2021). Microwave-assisted pyrolysis is based on the utilization of microwave radiation to generate heat inside the feedstock to achieve precise control and uniformity of the process reactions.

Pyrolysis temperature is an important factor influencing product distribution and quality (Singh et al., 2020). Higher pyrolysis temperature causes more secondary reactions that could reduce biochar and bio-oil yields and requires more energy consumption, while lower pyrolysis temperature may lead to incomplete devolatilization (Luo et al., 2021). Many studies focus on tuning the pyrolysis temperature to obtain desirable product distribution and high product quality (Chen et al., 2018a; Su et al., 2020). A pyrolysis temperature of ~500 °C has been suggested for most agro-residues to achieve the optimal conversion of lignocellulosic feedstocks (Wang et al., 2021; Zhu et al., 2018b). Furthermore, the trade-off between product quality and energy consumption needs to be considered to achieve better economic benefits in commercial-scale production.

2.3 Biochar production equipment

Biochar production depends not only on feedstock type, pyrolysis temperature, particle size, and moisture content, but is also closely related to the scale of production (Nsamba et al., 2015). In general, small-scale biochar production (less than 1 t/batch) can ensure high biochar yield and quality by adjusting the process with a low initial investment. However, large-scale biochar production has strict requirements considering continuous production and quality control, which requires high thresholds in the design, operation, and investment of pyrolysis reactors. Biomass pyrolysis is a technology that requires energy input, and the heat source (autothermal or allothermal mode) of the reactors is a key factor affecting the overall economics of biochar production (Arabiourrutia et al., 2020).

Typical reactor designs for biochar production include fixed bed, earthen kiln, rotary kiln, fluidized bed, auger reactor, and spouted bed (Arabiourrutia et al., 2020; Nsamba et al., 2015), as shown in Fig. 2. Fixed bed reactors are widely used in small-scale biochar production due to its ease of operation and design (Hjaila et al., 2013). However, the fixed bed has poor heat and mass transfer performance and only allows batch operation, limiting the scale of biochar production. The earthen kiln is a traditional and primitive biochar production method, in which the operating conditions are difficult to control with a long residence time (Smebye et al., 2017). A rotary kiln has a simple design and equipment operation, but the heat efficiency is still low (Yang et al., 2020).

Due to the gas-solid contact method, a fluidized bed has high heat transfer rates and gas-solid uniformity during pyrolysis (Chen et al., 2018b). The continuous operation of fluidized beds is beneficial to the large-scale production of biochar. However, the design and operation of fluidized beds are complex and require a large cost investment. It should be noted that the short residence time of biomass in the fluidized bed and the high conversion efficiency of carbon-to-gas result in lower biochar yields. Auger reactor can realize slow pyrolysis and fast pyrolysis by adjusting the screw feeding speed, with good heat transfer efficiency and simple operation control (Lakshman et al., 2021). Although the design of auger reactor is more complex than earthen kiln, it is considered a simple design compared to fluidized bed reactor.

Spouted bed has some similar characteristics to fluidized bed, such as high heat transfer rates and gas-solid contact (Azizi et al., 2020). Based on different solid-phase dynamics, the spouted bed can handle irregular particles, thus reducing the requirement for biomass grinding. The main product of biomass pyrolysis in the spouted bed is bio-oil, with a smaller amount of biochar generation. In addition, emerging reactors such as microwave reactors (Zulkornain et al., 2021) have been effectively applied to produce biochar, but are currently limited by the biochar production scale.

3. Goal and scope of life cycle assessment

Life cycle assessment is a useful tool for reducing carbon emissions and achieving carbon neutrality. The LCA literature on biochar production has increased by two folds in the last five years through Web of Science and Google Scholar analysis. In LCA, the goal and scope definition is the first step to be specified. There may be some slight differences in the goals, but all of the listed literature focus on the environmental impacts of production systems. Keywords include carbon footprint, GHG emissions, environmental performances, carbon sequestration potential, environmental impacts, air pollutants, environmental efficiencies and barriers, climate change and health effects (Table 2 and Table 3). Several studies also cover energy (Pourhashem et al., 2013), financial viability (Robb & Dargusch, 2018), and net economic aspects (Gong et al., 2020).

3.1 LCA methodology and impact categories

3.1.1 LCA methodology

The selection of calculation tool for LCA is one of the variables affecting the assessment results. The LCA calculation tools used by the authors are listed in Table 2. Due to the complexity of the life cycle assessment process, automatic calculation of the LCA software is a more convenient and faster approach (Arena et al., 2016). Typical LCA softwares include SimaPro, GaBi, and OpenLCA. However, it is noted that different softwares may lead to discrepancies in the results for the same LCI data (Herrmann & Moltesen, 2015). For manual calculation, Microsoft Excel and R software are feasible for evaluating simple impact categories (*e.g.*, global warming potential) (Lefebvre et al., 2021; Thakkar et al., 2016).

The Life Cycle Impact Assessment (LCIA) methodology is one of the important variables, depending on the selected impact categories, as listed in Table 2. Although different LCIA methodologies may have different mid-points and end-points, similar conclusions can be drawn from the majority of the literature. When only one impact category is assessed (*e.g.*, global warming potential), the IPCC methodology is often employed. As shown in Table 2, many studies have used the IPCC methodology to assess the impacts of biochar systems on climate change (Clare et al., 2015; Mohammadi et al., 2017).

3.1.2 Impact categories

Based on different LCIA methodologies, different impact categories such as carbon footprint, GHG emissions, carbon sequestration, carbon abatement, carbon balance, and global warming potential are used to assess climate change. Some researchers also consider other environmental issues, resource depletion, and human health, such as acidification potential, fossil fuel depletion potential, and human toxicity (Table 3). Parascanu et al. (2018) evaluated the cradle-to-grave environmental impacts of olives (agricultural olives production, olive oil extraction, and pyrolysis of olive pomace in Spain), consisting of 17 impacts subcategories. Using the CML methodology, Yang et al. (2021a) selected more impact categories to evaluate the carbon sequestration potential and environmental benefits of biochar production from crop residues. The results showed that biochar production was beneficial for most of the impact categories, except abiotic depletion potential and ozone depletion potential. The assessment of impact categories other than global warming potential depends on different geographic and social contexts.

3.2 Functional unit of agro-residue pyrolysis

The functional unit (FU) is the crucial foundation related to inputs and outputs, which provides a reference benchmark (Ubando et al., 2019); and it should be as far as possible related to the functions of the product rather than to its physical characteristics. Due to the diversity of functional units, different scenarios can be associated with different functional units, such as upstream flows (input feedstocks) and downstream flows (output products), resulting in difficulties in comparing different publications (Moreira et al., 2017). In biomass pyrolysis systems, the amount of feedstocks, biochar, bio-oil, and electricity are often selected as functional units (Table 2). For instance, 1 t of feedstock (dry basis or wet basis) and 1 t biochar are widely selected as the functional units, e.g., Yang et al. (2020) defined 1 kg of crop straw with an assumed 15% moisture content as the functional unit, while 1 kg of biochar (or activated carbon) was also used as the functional unit in some studies (Hjaila et al., 2013; Loya-González et al., 2019; Sepulveda-Cervantes et al., 2018). Some functional units are concerned with energy, such as 1 kg of bio-oil or 1 kWh of electricity generation (Chan et al., 2016; Pourhashem et al., 2013). Project benefits oriented functional units are also defined, such as average village household utilizing available cocoa waste (Sparrevik et al., 2014), 1 hectare of sugarcane crop (Lefebvre et al., 2021), and production of 1 kg of milled rice (Mohammadi et al., 2016). For the sake of comparison among different LCAs of biochar production, it is recommended to use 1 t feedstocks and 1 t biochar as the functional units.

3.3 System boundary of biochar production

The definition of system boundary is an important step in LCA, which includes four types:

cradle-to-grave, cradle-to-gate, cradle-to-cradle, and gate-to-gate. The production of biochar (or activated carbon) from agro-residues through pyrolysis is generally classified as cradle-to-grave or cradle-to-gate (Thers et al., 2019; Tiegam et al., 2021), as shown in Fig. 3. Agriculture cultivation is not included in the system boundary, mainly because the agro-residues are treated as waste streams (Yang et al., 2021a). In addition, some studies selected different start and end points for the system boundaries. Robb & Dargusch (2018) investigated the carbon footprint from oil palm plantation to biochar application in soil. Biomass production and harvest were also part of the system boundary in Cheng et al. (Cheng et al., 2020), Mo et al. (Mo et al., 2022), and Tiegam et al. (Tiegam et al., 2021). Righi et al. (2016) defined the system boundaries with additional consideration of fertilizer offset due to the removal of agro-residues. The definition of the system boundary significantly influences the assessment of material flows, energy flows, and emissions.

In biomass pyrolysis to produce biochar, side flows of bio-oil and syngas are worthy of attention. In general, the system expansion approach is used to deal with side flows, such as the use of heat and electricity from bio-oil and syngas (Azzi et al., 2019; Yang et al., 2021a). The value-added utilization of bio-oil and syngas will avoid fuel consumption, thereby reducing emissions. However, in some cases, the bio-oil and syngas are not utilized due to the equipment limitations (*e.g.*, traditional earthen kiln) (Smebye et al., 2017).

The construction of a pyrolysis plant is an important focus, yet many studies have not paid attention to its analysis due to the unavailable data of infrastructure establishment and plant operation. For future large-scale pyrolysis equipment or integration with power plant or biorefinery plant (Azzi et al., 2019; Yang et al., 2020), it is essential to include the construction, operation, and maintenance phases in the life cycle assessment (Yang et al., 2021a).

The avoided use of fuel and/or fertilizer has been included in the life cycle assessment in some studies, which could significantly mitigate fossil depletion and freshwater eutrophication. Thers et al. (2019) were concerned with the avoided electricity production and the saving in fossil fuel consumption. Pourhashem et al. (2013) assessed the carbon credit associated with avoided GHG emissions owing to biochar replacing coal in electricity generation. Muñoz et al. (2017) considered the reduced urea application resulting from biochar application as a bio-based fertilizer in the soil environment.

Environmental analysis is often combined with economic analysis to assess the proposed systems in terms of sustainability and profitability, providing better support for decision-makers. In general, the boundary system of environmental assessment coincides with that of economic analysis (Dutta & Raghavan, 2014). However, in the study of Robb & Dargusch (2018), the system boundary of carbon footprint exceeded that of financial assessment, the latter only focused on the pyrolysis process and soil application of oil palm empty fruit bunch.

There are several typical scenarios for agricultural waste management. Alternative energy source, soil amendment, and use as adsorbent (substitute of activated carbon) are all potential options for neutralizing the environmental impacts of agricultural waste (Fig. 3). Although biochar was not the main focus in some studies (Chan et al., 2016; Negro et al., 2017), the development of comprehensive utilization scheme of agricultural waste could still be accomplished.

3.4 Life cycle inventory of biochar production

3.4.1 Inventory data analysis

Life Cycle Inventory (LCI) is used to compile and quantify all the inputs and outputs of the systems (Ubando et al., 2019; Vienescu et al., 2018). The source and selection of data are essential, which determine the validity and uncertainty of the LCA. The sources of data include literature, databases (e.g., Gabi Professional Database, Ecoinvent Database), government reports, company statistical yearbooks, simulations, calculations, experiments, expert opinions, field survey, questionnaires, interviews, etc. (Prasad et al., 2020; Rebello et al., 2020). Direct data from field-scale applications should always be preferred over indirect data or data from smaller-scale investigations. Data sources from representative articles are presented in Table 2. In general, the data reflecting the actual local conditions are preferred, but it is difficult to collect data for all process units. Similar data sources and backgrounds from relevant literature and databases are feasible alternatives. It should be noted that many LCA databases are developed in consideration of the environment in Europe and North America, in other words, insufficient local data may compromise the accuracy of the assessment.

It is not uncommon that, when analyzing the LCA of the selected system in a specific country or region, the missing data could be supplemented with the data from other regions. Yang et al. (2021a) analyzed the carbon sequestration and environmental benefits of grain residues by citing the related data from other countries due to the lack of data in the selected system. It is worth noting that the environmental parameters can vary widely across different geographical locations;

therefore, the selection of similar region and climate is advocated. In some studies, simulations are considered as the data sources due to the experimental limitations (Pourhashem et al., 2013; Yang et al., 2020). Aspen Plus, a commercially available software for simulating biomass conversion, is widely used to obtain the process parameters of biomass pyrolysis (Mo et al., 2022; Parascanu et al., 2018). Government reports and company statistical yearbooks are also important data sources for LCA, which can reflect the overall situation of a region (Dai et al., 2020). In addition, questionnaires, interviews, and field survey are promising ways to obtain the LCA data. The field data collection combined with official statistics can address the system incompatibilities. Although different data sources can lead to discrepancy in quantitative results of LCA for the selected systems, the general conclusions often remain qualitatively the same (Cen et al., 2022).

3.4.2 Life cycle inventory analysis

The types of feedstock affect the assessment accuracy of the biochar production system. Different feedstocks have different physicochemical properties, resulting in variable yield and quality of biochar. Typical feedstocks for biochar production are listed in Table 2, and the selection of agro-residues feedstocks is closely related to the regional characteristics. In China, crop residues are widely used as feedstock to produce biochar. In Spain, olive waste is widely selected as feedstock. In Vietnam, rice husk is commonly utilized. In Indonesia, cocoa waste is a typical biochar feedstock. In Malaysia, oil palm kernel shell and oil palm empty fruit bunches are easily obtained in large quantities as feedstocks. Thus, agro-residues are agricultural side flows that are locally abundant and readily accessible within a short distance.

As a secondary aspect of LCA in biochar production, collection and transportation result in significant amount of energy consumption and GHG emissions. Collection depends on the types of agro-residues, primary agro-residues need to be collected first, and secondary agro-residues come from the side streams of agro-processing. Thakkar et al. (2016) included the collection of agro-residues in the system boundary of the LCA, whereas El Hanandeh (2015) did not include the collection phase in the LCA system boundary. The transportation phase is closely related to the distribution of pyrolysis equipment. Chan et al. (2016) assumed a 100-km transportation distance from the oil palm plant to the pyrolysis plant using diesel trucks. Llorach-Massana et al. (2017) set a transport distance of 25 km. Yang et al. (2020) adopted a distributed pyrolysis system with an average transport distance of 20 km. When biochar is used for soil amendment or remediation, it is indispensable to transport the biochar from the pyrolysis plant to the field.

Pretreatment mainly depends on the requirements of pyrolysis equipment and product quality. The drying process that consumes notable amount of energy has been included in the system boundary (Llorach-Massana et al., 2017). To obtain higher quality biochar, grinding pretreatment of feedstocks may be required, especially for fluidized bed reactors. It is also noted that torrefaction pretreatment is often applied to improve the bio-oil quality in subsequent pyrolysis (Cen et al., 2021).

Pyrolysis conditions and techniques are the critical factors for biochar production. Heating rate, pyrolysis temperature, and residence time significantly affect the pyrolysis of agro-residues. Muñoz et al. (2017) investigated the LCA of biochar produced from the pyrolysis of agro-residues at 300, 400, and 500 °C. For example, 350-400 °C was considered an optimum temperature for increasing the biochar yield from tomato plant residue (Llorach-Massana et al., 2017). Fast pyrolysis, intermediate pyrolysis, slow pyrolysis, and gasification technology for biochar production were compared (Gong et al., 2020), of which the results showed that different pyrolysis techniques had distinctive optimal carbon offset benefits for various feedstocks, e.g., intermediate pyrolysis for rice straw and slow pyrolysis for corn stover. Using different equipment to produce biochar affects the life cycle inventory configuration and the LCA results. Smebye et al. (2017) compared flame curtain kilns to earthen kilns, retort kilns, and pyrolytic cook-stoves, of which the pyrolytic cook-stoves exhibited the most positive environmental benefits in the LCA. Therefore, choosing suitable and application-oriented pyrolysis conditions and technologies is essential in LCA of biochar production.

When biochar is used for soil amendment or remediation, more factors are involved in the environmental performance of the biochar system, such as the application rate of biochar in soil, the stability of the biochar, and the effects of biochar on the soil environment (Sun et al., 2022a). The application rate of biochar in the soil varies in different publications, e.g., a biochar dosage of 20 t/ha was used in (Muñoz et al., 2017), while it was 5 and 10 t/ha under different scenarios in (Qin et al., 2016). Biochar application rate may affect the crop production, and a high dosage of biochar may adversely inhibit the plant growth.

The stability of biochar is closely related to the physicochemical properties of biochar and soil environment. The unstable components inside the biochar could decompose within a few years, while the stable carbon remains in the soil for an extended period of time (Sun et al., 2021). In Mohammadi et al. (2016), 69% of the carbon was assumed to be stable, while 31% of the unstable carbon was released into the atmosphere within five years. The 80% stable carbon in the biochar was also used as a criterion for biochar stability in soil (Muñoz et al., 2017; Sparrevik et al., 2014). The effects of biochar on soil include increased soil fertility, pollutants adsorption, improved soil conditions, enhancement on soil biota, and increased crop yield (Lehmann et al., 2021). Yang et al. (2020) reported that the addition of biochar increased the fertilizer efficiency by 7% and crop yield by 20%. Furthermore, the addition of biochar can reduce methane and N_2O emissions, mitigating the climate change (Li et al., 2022). Nevertheless, the putative benefits of biochar addition in soil may vary in LCA cases.

4. Life cycle impact assessment

Life cycle impact assessment is an integration of quantitative and qualitative description and evaluation of the environmental impacts based on inventory analysis of the selected systems. Environmental impacts are characterized through impact classification and quantitative analysis.

4.1 Impact assessment results

As shown in Table 3, the system boundaries, functional units, and pyrolysis systems are various in the literature, resulting in a difficult comparison of LCA results. Climate change as the main indicator in the LCA is included in all selected literature, while other impact factors (e.g., PED, AP, EP) are only considered in some studies. Both negative values (CO_2-eq sequestration) and positive values (CO_2-eq emissions) are reported in the results of LCA, which are related to the system boundary of LCA. For example, Dai et al. (2020) reported a GHG emission reduction potential of 1.41×10^6 t CO_2-eq based on the supply data of Chinese crop residue. Clare et al. (2015) reported a GWP of -1.06 t CO_2-eq/t feedstock.

By extending the system boundary to biochar application, the LCA results showed that CO_2-eq sequestration could be realized. When the system boundary of the LCA excluded biochar applications, CO_2-eq emissions were reported (Loya-González et al., 2019; Mo et al., 2022; Tiegam et al., 2021). Righi et al. (2016) compared the carbon reduction of biochar used for soil amendment (-386 to -933 kg CO_2-eq/t feedstock) and energy supply (-240 to -787 kg CO_2-eq/t feedstock). However, Pourhashem et al. (2013) revealed -217 g CO_2-eq/kW·h electricity for cofiring biochar and -84 g CO_2-eq/kW·h electricity for soil amendment. The carbon reduction benefits are prominent when biochar is used for different applications. It is clear that the GHG emissions caused by biomass pretreatment and biochar production can be neutralized by the benefits of biochar applications (via carbon sequestration).

4.2 Biochar production

4.2.1 Effect of agro-residue types

Various agro-residues (empty fruit bunch, corn stovers, cocoa shells, etc.) were analyzed in Table 2 and Table 3. It can be proved that agro-residues derived from crop side flows are suitable feedstocks for biochar production in terms of environmental benefits. The utilization of biochar is beneficial to the management of agro-residues (He et al., 2022). As a waste source, GHG emissions from agro-residues production are generally not included in the biochar production system. Theoretically, the secondary agro-residues require less collection effort than the primary agro-residues (Yang et al., 2021a). Therefore, the impact of the collection stage is minor, which sometimes is not clearly stated in the LCA of biochar production from agro-residues (Lefebvre et al., 2021).

The moisture contents of agro-residues vary in different stages, such as harvest stage and natural drying stage. High moisture content in agro-residues requires more energy consumption for drying and increases GHG emissions. For example, when wet orange peel waste was used as feedstocks for biochar production, its carbon reduction (-5.5 kg CO_2-eq/t wet feedstock) was marginal (Negro et al., 2017). Nevertheless, overall carbon reduction can still be achieved using different agro-residues for biochar production.

4.2.2 Effect of pyrolysis parameters

Pyrolysis conditions such as temperature, pyrolysis rate, and residence time have shown clear impacts on the product distribution and properties (He et al., 2021b; Zhu et al., 2019b). It is difficult to directly compare different LCA cases considering the differences in feedstocks and pyrolysis systems. Cheng et al. (2020) reported the carbon emissions of biochar produced from crop residues at different temperatures (400, 550, 700 °C), in which the avoided carbon emissions ranged from -200 to -470 kg CO_2-eq/t feedstock. Thers et al. (2019) found that the carbon reduction of biochar obtained at 400 °C and 800 °C were -392 and -429 kg CO_2-eq/t dry seed, respectively. In addition, for rice straw, the CO_2 reductions were 1.14, 1.64, and 1.10 t CO_2-eq/t feedstock through fast pyrolysis, intermediate pyrolysis, and slow pyrolysis, respectively, whereas for corn stover, they were 1.75，1.12 and 1.84 t CO_2-eq/t feedstock, respectively (Gong et al., 2020). Therefore, the CO_2 reduction is related to not only the pyrolysis rate but also the feedstock type. The residence time generally has a significant influence on the yield and properties of biochar at low pyrolysis temperatures (Cheng et al., 2020). Pyrolysis conditions also affect the biochar yield and co-product distribution (bio-oil and syngas), resulting in variable energy offsets (Matuštík et al., 2020). Furthermore, the proportion of stable carbon in biochar is an important factor for effective carbon sequestration in soil amendment.

4.2.3 Effect of pyrolysis equipment

As shown in Table 3, different regions have specific requirements for biochar production systems, and large-scale centralized pyrolysis systems and small-scale portable pyrolysis reactors need to be balanced. Large-scale pyrolysis plants have higher pyrolysis efficiency and co-product energy offsets, while small-scale reactors may be unable to utilize the pyrolysis co-products and even incur the adverse effects such as particulate emissions and air pollution. It should be noted that manpower requirements are generally not included in the system boundary of LCA studies. Small-scale pyrolysis reactors are labour-intensive and require more effort to produce the same amount of biochar.

In addition, transportation distance is an important factor restricting the choice of pyrolysis device. The benefits of large-scale centralized pyrolysis plants can be outweighed by long-distance transportation. For example, Yang et al. (2020) investigated the environmental impacts of the distance and mode of transportation, trucks were used for short-distance transport (20 km) while trains were used for long-distance transport (170 km). Long transportation distances had a negative effect on net GWP. Mohammadi et al. (2016) reported that the carbon footprints of pyrolytic cook-stove and drum ovens were 1.11 and 3.85 kg CO_2-eq/kg milled rice, respectively. Mohammadi et al. (2017) revealed more GWP of biochar production equipment, for example, -229 kg CO_2-eq/t dry rice husk for brick kiln, -318 kg CO_2-eq/t dry rice husk for stove, and -360 kg CO_2-eq/t dry rice husk for large-scale pyrolysis plant. In general, advanced pyrolysis equipment leads to greater environmental benefits in terms of the reduction of CO_2 emissions. However, in developing regions, the choice of a suitable pyrolysis technology is crucial. Advanced pyrolysis equipment may not necessarily be desirable due to economic constraints. Small-scale portable pyrolysis reactors can also provide notable benefits by replacing primitive earth mound kilns that have negative environmental impacts (Smebye et al., 2017).

4.3 Sensitivity analysis

Sensitivity analysis is critical for revealing the reliability and robustness of LCA, as shown in Table 3. When biochar is applied to soil remediation, many uncertainties are considered, such as the degradation rate, electricity supply, N_2O mitigation, carbon stability, timespan, avoided fertilizer use, CH_4 emissions, etc. Robb & Dargusch (2018) found that the nutrient retention of biochar did not change between 1 and 20 years, beyond the default assumption of 5-year persistence. Sparrevik et al. (2014) revealed the environmental impact of the uncertainty of stable carbon in soil. The stability of biochar in soil depends on many intertwined factors, such as biochar characteristics, climate, and soil type.

The biochar yield (10-70%) is one of the most important uncertainties affected by the feedstock types, pyrolysis conditions, and technology. Yang et al. (2021a) demonstrated that all of the parameters (biochar yield, biochar carbon content, and electricity conversion efficiency of bio-oil and syngas) directly influenced GWP. In addition, energy consumption and thermal efficiency are sensitive factors for biochar production. The change in bio-oil and syngas yield is more sensitive to the environmental impacts (such as GWP) due to the avoided emissions from the traditional energy sources (Chan et al., 2016). The size of the pyrolysis reactor was also a critical consideration (Righi et al., 2016). The uncertainty of transportation distance could affect the environmental benefits of biochar production (El Hanandeh, 2015; Yang et al., 2020). Furthermore, Arena et al. (2016) considered a ±10% variation in energy consumption related to feedstock and biochar processing in a sensitivity analysis.

5. Prospects and challenges

Biochar production from agro-residues is an environmentally friendly and sustainable approach, and LCA can assist in quantifying the potential of biochar utilization and fostering an efficient production management. Multi-purpose applications of biochar can promote carbon sequestration, energy recovery, and conversion to value-added products (e.g., adsorbents). Due to regional climate and social factors, there are differences in the availability, quantity, and type of agro-residues (He et al., 2022). Large amounts of locally accessible agro-residues are suitable for large-scale pyrolysis equipment, while batch production or portable instrument is more beneficial for small amounts of available agro-residues originating from remote areas. The production process of biochar should adapt to localization or regionalization for maximum environmental benefits with reference to LCA results. Inadequate removal of agro-residues from the field may result in the reduction of soil nutrients, depletion of soil organic carbon, and soil erosion. Thus, extended system boundary and more inventory considerations need to be comprehensively integrated in the LCA of biochar production from agro-residues. Robust frameworks and international guidelines are available for promoting consistency in the carbon assessments with sector-specific rules (e.g., PAS 2050 (2008); ISO14067 (2018); WRI/WBCSD (2011)). However, they may apply different criteria and still result in different outcomes despite sharing the same general principles.

A taxonomy of different types of biochar products for various conventional and emerging applications is of the utmost importance to impart desirable biochemical properties to biochar with the least environmental impacts. Although there are signs that certain biochar systems are capable of fulfilling the "triple win promise" (energy, climate, and food), evidence does not indicate that biochar system will work as a silver bullet across large areas; in other words, the local context and case-specific boundary conditions should be adequately taken into account.

The economic sustainability analysis (encompassing financial costs and benefits) is encouraged in the environmental assessment to optimize the production flows for sustainable biochar production. From a circular economy perspective, the utilization of system co-products (bio-oil and syngas) should be included in the LCA of biochar production, further expanding the potential for biochar production from agro-residues towards carbon-efficient resource circulation. The development of biochar poly-generation can maximize the economic benefits of agro-residues while mitigating the environmental burdens of biochar production. Moreover, a higher proportion of green energy utilization in the production of biochar can achieve more prominent environmental benefits, which is an important direction in practical applications.

6. Conclusions

This study scrutinized the LCA of biochar production from different agro-residues and typical pyrolysis technologies. Although the functional units and system boundaries of different cases are variable, currently available studies reveal that biochar has a good carbon reduction potential in scenarios such as alternative energy source, soil amendment, and activated carbon substitution. It is important to customize the pyrolysis design of biochar production for better environmental and economic benefits with respect to local/regional context. Overall, biochar has proved to be a promising avenue to achieve carbon-smart management of agro-residues in the nexus of agroecosystem, climate change, and economic sustainability.

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CRediT authorship contribution statement

Xiefei Zhu: Conceptualisation, Methodology, Data curation, Formal analysis, Investigation, Visualisation, Writing–original draft. **Claudia Labianca:** Methodology, Validation, Writing - review & editing. **Mingjing He:** Methodology, Validation, Writing - review & editing. **Zejun Luo:** Investigation, Methodology, Validation, Visualisation, Writing–review & editing. **Chunfei Wu:** Validation, Writing - review & editing. **Siming You:** Validation, Writing - review & editing. **Daniel C.W. Tsang:** Resources, Conceptualisation, Methodology, Validation, Supervision, Project administration, Funding acquisition, Writing–review & editing.

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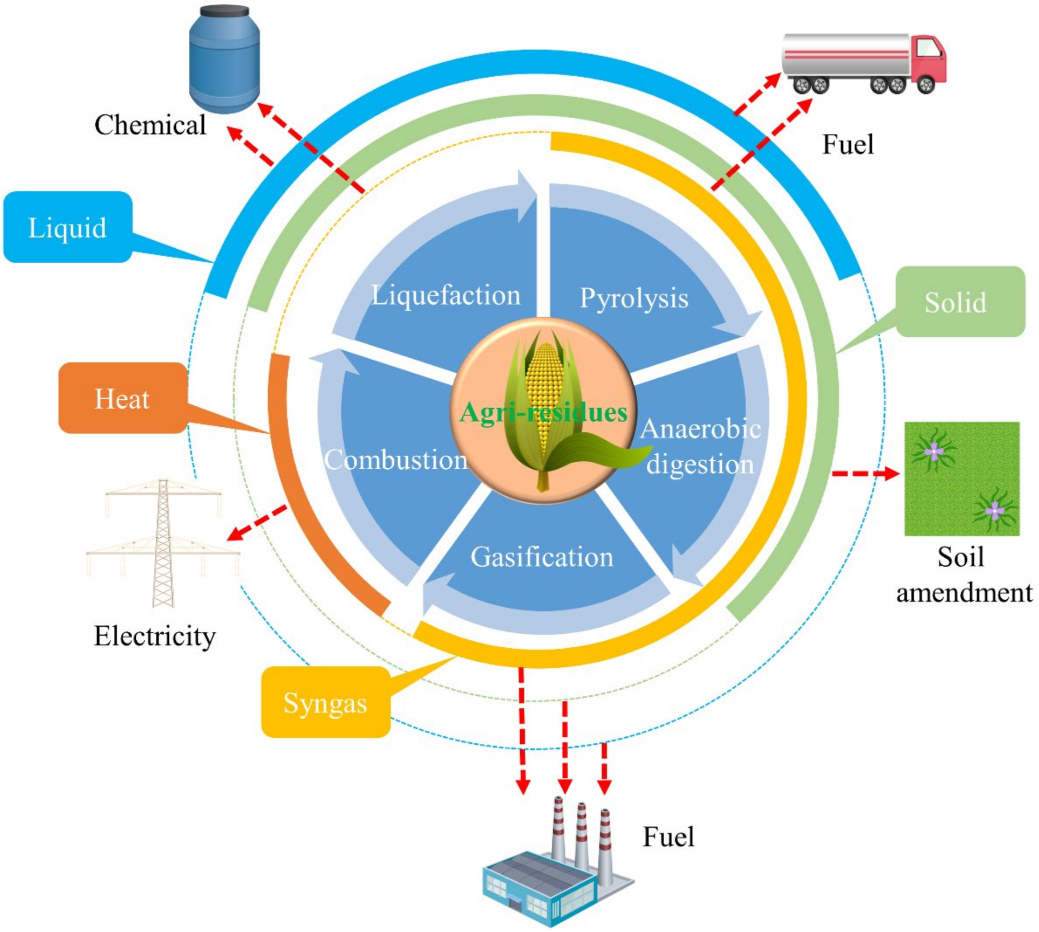

Fig. 1. Typical conversion technologies of agro-residues.

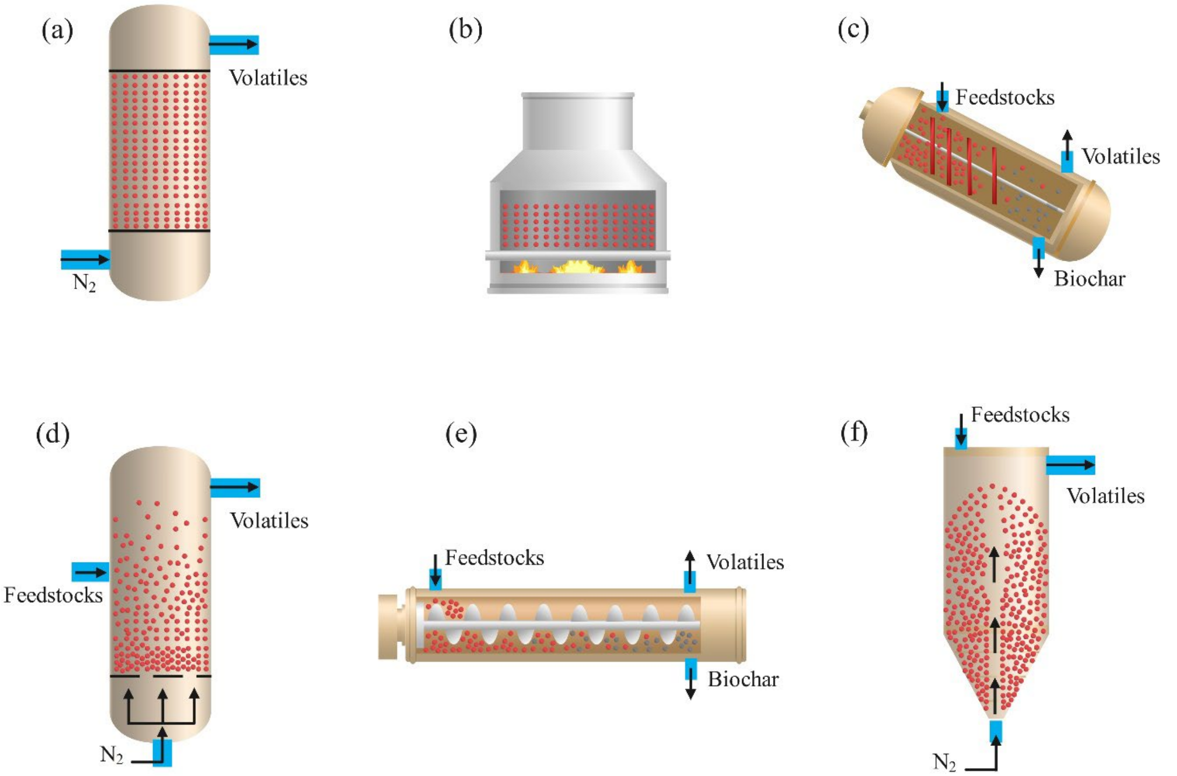

Fig. 2. Typical biochar production reactors: (a) fixed bed, (b) earthen kiln, (c) rotary kiln, (d) fluidized bed, (e) auger reactor, and (f) spouted bed.

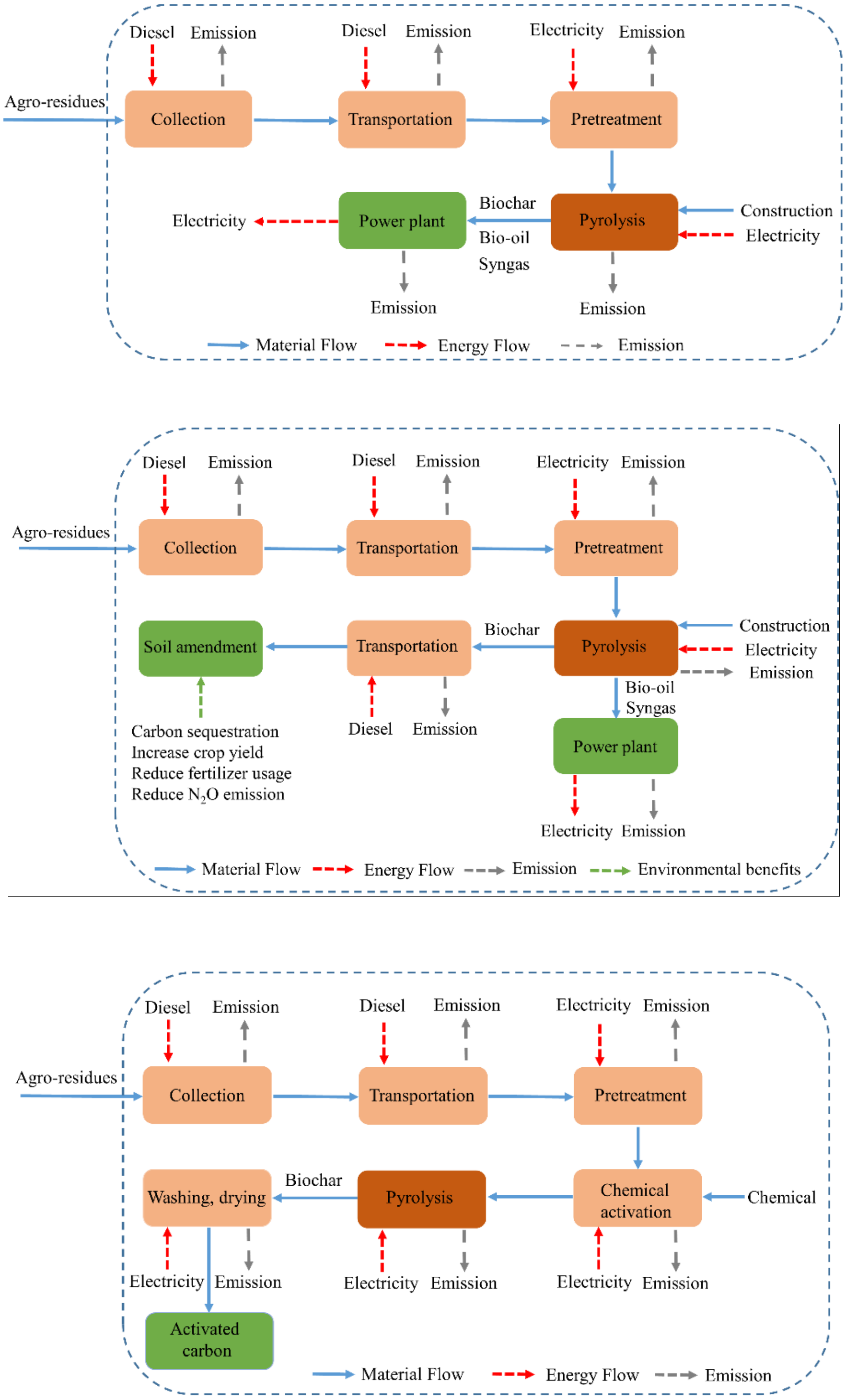

Fig. 3. System boundary of life cycle assessment: (a) alternative energy source, (b) soil amendment, and (c) activated carbon substitution.

Table 1. Proximate and ultimate analyses and HHV of different agricultural wastes

Samples		Moisture (%)	Volatile (%)	Fixed carbon (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)	HHV (MJ/kg)	References
Primary agro-waste	Rice straw	-	71.60	14.80	13.60	40.30	4.60	40.70	0.80	16.20	Cen et al. (2021)
	Rice straw	6.50	60.50	20.10	13.00	41.30	6.10	37.60	1.00	-	Singh et al. (2020)
	Cotton stalks	-	78.65	12.92	8.43	47.43	3.09	39.79	1.27	-	Wang et al. (2019)
	Cotton stalks	6.80	69.83	22.03	1.34	46.43	6.31	44.98	0.60	-	Lu et al. (2021)
	Wheat straw	7.57	66.56	16.17	9.70	47.30	6.30	45.28	1.01	-	Zhao et al. (2020)
	Wheat straw	-	73.50	16.44	10.06	43.00	5.36	40.73	0.63	17.81	Chang et al. (2018)
	Corn straw	-	73.42	16.35	10.23	42.56	5.05	41.16	0.87	17.56	Chang et al. (2018
	Corn straw	2.16	77.64	17.52	2.68	40.67	5.51	52.94	0.79		Chen et al. (2018b)
	Palm fronds	6.26	73.91	14.65	5.18	43.74	5.64	45.13	0.31	16.78	Chantanumat et al. (2022)
	Palm fronds	4.83	70.33	18.97	5.87	41.00	6.74	51.24	0.67	16.00	Thu et al. (2021)
	Palm trunk	6.78	76.66	11.59	4.97	41.57	5.55	47.79	0.11	15.49	Chantanumat et al. (2022)
Secondary agro-waste	Rice husk	5.60	64.90	18.40	11.10	43.30	3.20	40.90	0.80	-	Singh et al. (2020)
	Rice husk	-	71.00	17.10	11.90	35.44	4.77	42.41	0.26	15.76	Su et al. (2020)
	Palm kernel shell	-	75.21	22.74	2.05	50.73	5.97	40.83	0.36	20.35	Chang et al. (2018)
	Palm kernel shell	4.52	75.88	16.86	2.74	50.19	6.05	40.05	0.92	21.01	Chantanumat et al. (2022)
	Palm shell	4.70	73.50	19.20	8.60	52.05	5.37	42.10	0.49	19.94	Thu et al. (2021)
	Palm fiber	-	74.83	22.49	2.68	46.71	6.08	43.76	0.70	18.84	Chang et al.(2018)
	Palm fiber	8.60	78.00	7.60	5.80	45.38	10.59	42.04	1.32	17.00	Thu et al. (2021)
	Walnut shell	-	76.88	21.65	1.47	50.13	6.13	41.93	0.32	19.02	Chang et al. (2018)
	Walnut shell	1.06	74.53	22.05	2.36	61.09	6.42	29.81	0.16	-	Zhu et al. (2018b)
	Empty fruit bunch	3.37	76.16	16.36	4.11	45.51	5.57	44.05	0.72	18.09	Chantanumat et al. (2022)
	Empty fruit bunch	7.95	83.86	10.78	5.36	49.07	6.48	38.29	0.70	19.35	Thu et al. (2021)

Table 2. Summary of LCA methods

References	Feedstocks	Country /region	LCA software	LCIA methodology	Functional Units	Data sources
Robb & Dargusch (2018)	Empty fruit bunch	Indonesia, Australia	NR	NR	1 t biochar	Literature
Righi et al. (2016)	Corn stovers	Italy	GaBi 6	CML method	1 t dried corn stovers	Experiments; databases
Thers et al. (2019)	Oilseed rape straw residues	Danish	NR	IPCC 2006	1 t dry seed	Calculations, reports
Yang et al. (2021a)	Crop residues	China	GaBi 8.70	CML 2001	1 t crop residues	Literature, government statistics
Chan et al. (2016)	Empty fruit bunch	Malaysia	NR	NR	1 kg bio-oil	Literature
Sparrevik et al. (2014)	Cocoa shells	Indonesia	NR	NR	An average village household utilizing available cocoa waste	Literature, databases
Cheng et al. (2020)	Crop residues	United States	NR	NR	1 t feedstocks	Literature
Llorach-Massana et al. (2017)	Tomato plant residue	Spain	NR	IPCC 2013	1 t biochar	Experiments, literature
Clare et al. (2015)	Straw	China	NR	IPCC 2007	1 t feedstocks	Literature, expert opinion
Pourhashem et al. (2013)	Corn stover	United States	SimaPro 7.2	IPCC 2006	1 kW·h bio-oil-derived electricity	Databases, simulation, literature, experiments
Gong et al. (2020)	Rice straw	China	NR	IPCC 2006	1 t feedstocks	Literature, government statistical
Gong et al. (2020)	Corn stover	China	NR	IPCC 2006	1 t feedstocks	Literature, government statistical
Sepulveda-Cervantes et al. (2018)	Soybean shells	Mexico	SimaPro 8.0	ReCiPe endpoint	1 kg activated carbon	Experiments, databases
Dai et al. (2020)	Crop residue	China	NR	MUIO-LCA model	1 t feedstocks	Statistical yearbook
Yang et al. (2020)	Agricultural straw	China	SimaPro 9.0	CML 2	1 kg crop straw (15% moisture content)	Statistical yearbook, simulation, literature
El Hanandeh (2015)	Olive solid waste	Australia	OpenLCA	ReCiPe Midpoint	1 t olive solid waste	Literature, databases

Parascanu et al. (2018)	Olive pomace	Spain	SimaPro 8.2	ReCiPe Mid-point and End-point	100 kg olive pomace	Company, simulation
Hjaila et al. (2013)	Olive-waste cakes	Spain	Simapro 7.3	CML 2	1 kg activated carbon	Experiments, literature, databases, company report
Mo et al. (2022)	Oil palm kernel shell and empty fruit bunches	China	Gabi	NR	1 kg of biofuel	Simulation, databases
Negro et al. (2017)	Orange peel waste	Italy	NR	CML 2002	1 t orange peel waste (wet weight).	Literature, databases, estimations, expert opinion
Mohammadi et al. (2016)	Rice straw and husk	North Vietnam	SimaPro 8.0.1	IPCC 2006	1 kg milled rice	Databases, report
Mohammadi et al. (2017)	Rice husk	Vietnam	SimaPro 8.0.1	IPCC 2006	1 t dry rice husk	Questionnaires and interviews, literature, databases, reports
Arena et al. (2016)	Coconut shells	Indonesia	GaBi 6.0	CML-2001	1 t activated carbon	Literature, company, databases
Loya-González et al. (2019)	Corn pericarp	Mexico	SimaPro 8.0	ReCiPe	1 kg activated carbon	Experiments, databases
Tiegam et al. (2021)	Cocoa pods	Cameroon	SimaPro 9.0.0.49	ReCiPe Midpoint	4 g activated carbon	Experiments, company
Thakkar et al. (2016)	Wheat, barley, oat straw	Canadian	NR	NR	1 t dry straw	Literature
Lefebvre et al. (2021)	Sugarcane residues	South America	R software version	IPCC 2013	1 ha sugarcane crop	Publicly available data
Dutta & Raghavan (2014)	Corn stover	Canada	Microsoft Excel	IPCC 1996	1 t dry biomass	Government statistical, literature, reports
Muñoz et al. (2017)	Oat hulls	Chile	SimaPro 8	ReCiPe midpoint	1 t biochar	Field collections, experiments, databases, literature

NR: not reported or found in the article

Table 3. Summary of LCA results

References	Impact categories	Sensitivity analysis	LCA results (per functional unit)	Pyrolysis reactor
Robb & Dargusch (2018)	Carbon footprint	Yes	-691 kg CO_2-eq when used to influence crop yield, -286 kg CO_2-eq when used to reduce fertilizer requirements.	Pyrolysis reactor
Righi et al. (2016)	GWP, PED, AP, EP, AD	Yes	-240 to -787 kg CO_2-eq for combustion, -386 to -933 kg CO_2-eq for soil amendment	Pilot-scale pyrolyzer
Thers et al. (2019)	GHG emission	Yes	Contributions of -392 and -429 kg CO_2-eq in the BC-400 and BC-800 scenarios	Pyrolysis plant
Yang et al. (2021a)	GWP, AP, EP	Yes	GWP (-921.30 kg CO_2-eq)	Pyrolysis plant
Chan et al. (2016)	GWP, AP, EP, HT	Yes	GWP (-4.46 kg CO_2-eq)	Fluidized bed reactor
Sparrevik et al. (2014)	Climate change impacts	Yes	-26 eco points	Retort technology
Cheng et al. (2020)	GWP	No	-200 to -470 kg CO_2-eq	Auger-based reactor
Llorach-Massana et al. (2017)	Carbon footprint	No	Carbon sink between 21 and 155 kg CO_2-eq.	Pilot-scale
Clare et al. (2015)	GWP	Yes	-1.06 t CO_2-eq	Pyrolysis
Pourhashem et al. (2013)	GWP	Yes	-217 g CO_2-eq for cofiring biochar, -84 g CO_2-eq for land amendment	Small-scale fast pyrolysis
Gong et al. (2020)	GWP	Yes	-1.101 to -1.636 t CO_2-eq under slow pyrolysis to fast pyrolysis	Fluidized bed for fast pyrolysis
Gong et al. (2020)	GWP	Yes	-1.122 to -1.839 t CO_2-eq under slow pyrolysis to fast pyrolysis	Fluidized bed for fast pyrolysis
Sepulveda-Cervantes et al. (2018)	GWP	Yes	5.86 to 47.15 kg CO_2-eq	Electric furnace into a quartz reactor
Dai et al. (2020)	GHG reduction potential	Yes	Total GHG reduction potential 1.41×10^{6} t CO_2-eq based on Chinese corp residue supply in 2012	NR
Yang et al. (2020)	GWP, AD, AP, EP	Yes	GWP (-0.62 kg CO_2-eq), AD (2.70×10^{-3} kg Sb-eq), AP (2.49×10^{-3} kg SO_2-eq), EP (1.53×10^{-3} kg PO_4^{-3}-eq)	kiln, centralized pyrolysis system

El Hanandeh (2015)	GWP	Yes	GWP (-130 kg CO_2-eq)	Mobile pyrolysis units
Parascanu et al. (2018)	CC, HT, TETP, FET, FD	No	CC (3.39×10^6 kg CO_2-eq), HT (1.16×10^6 kg 1.4-dB-eq), FET (8.65×10^4 kg 1.4-dB-eq), FD (8.69×10^5 kg oil-eq)	Pyrolysis plant
Hjaila et al. (2013)	GWP, ADP, AP, EP	Yes	GWP (11.10 kg CO_2-eq), ADP (0.079 kg Sb-eq.), AP (0.108 kg SO_2-eq.), EP (0.033 kg PO_3^{-4}-eq.)	Steel reactor
Mo et al. (2022)	GWP, HT, TETP, AP	No	GWP (0.988 kg CO_2-eq), HT (0.003 kg 1,4-DCB-eq), TETP (0.082 kg 1,4-DCB-eq), AP (0.003 kg SO_2-eq)	Modeled pyrolysis reactor
Negro et al. (2017)	GWP	No	-5.5 kg CO_2-eq	Fast pyrolysis reactor
Mohammadi et al. (2016)	Carbon footprint	Yes	1.11 CO_2 eq for pyrolytic cook-stove and 3.85 kg CO_2-eq for drum oven	Pyrolytic cook-stove and drum oven
Mohammadi et al. (2017)	GWP	Yes	-318 kg CO_2-eq for stove, -229 kg CO_2-eq for brick kiln and -360 kg CO_2-eq for BigChar 2200 unit	Stove, brick kiln, and BigChar 2200 unit.
Arena et al. (2016)	GWP, HT, AP	Yes	GWP (2.1×10^{-11} person equivalent), HT (1.2×10^{-10} person equivalent), AP (4.1×10^{-11} person equivalent)	Modern facility equipped
Loya-González et al. (2019)	Environmental impact, FD, HHCC, PMF	No	Environmental impact (8.73 Pt), FD (4.42 Pt), HHCC (2.38 Pt), PMF(0.95 Pt)	Tube furnace
Tiegam et al. (2021)	GWP	No	4.63 kg CO_2-eq	Furnace
Thakkar et al. (2016)	Net carbon sequestration	No	0.204 t CO_2-eq for the centralized system; 0.141 to 0.217 t CO_2-eq for the portable systems	Centralized plant, portable systems
Lefebvre et al. (2021)	GWP	Yes	-6.3 ± 0.5 t CO_2-eq	Industrial slow pyrolyzer
Dutta & Raghavan (2014)	Net climate change impact	Yes	-1100 Tg CO_2-eq/ha for soil, -1900 Tg CO_2-eq/ha for electricity	Slow pyrolysis reactor
Muñoz et al. (2017)	GWP	Yes	-2.59 t to -2.70 t CO_2-eq	Pilot-scale pyrolyzer

GWP: Global Warming Potential, PED: primary energy demand from non-renewable resources, AP: acidification potential, EP: eutrophication potential, AD: abiotic depletion, HT: human toxicity, TETP: terrestrial ecotoxicity potential, HHCC: human health climate change, PMF: particulate matter formation, FET: freshwater ecotoxicity, NR: not reported.