Chapter 2: Sustainability considerations of biochar production in biowaste management

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Abstract

Large volumes of biowastes including municipal solid waste, agricultural residues, animal manure and biosolids are generated continually with the growth of global population. These biowastes can pose a huge threat to the ecosystem and human health if managed inappropriately. Commonly, conventional strategies for biowastes management such as burning, open dumpling and landfilling can cause a lot of environmental issues like greenhouse gas emissions, water and soil pollutions that are hazardous to all living beings including humans. However, these biowastes can be considered as valuable resources if they are handled responsibly that will not only reduce the problem of biowastes management, but also generate value-added products and bioenergy to meet the ever-increasing resource and energy demands. The conversion of biowastes to biochar with the production of bio-oil as byproducts have been considered as a potential alternative for biowastes management, which is economically viable and environmentally sustainable. This chapter focuses on sources and of biowastes, the comparison of environmental impacts of biowaste management between biochar productions and the conventional management methods, as well as technologies for the sustainable biochar production from biowastes. Furthermore, environmental benefits of biochar production from biowastes are discussed in this chapter as well. Future perspectives on commercial biochar production from biowastes is discussed.

Keywords: Biochar, biowaste management, biocahr production technology, life-cycle assessment, climate change

1. Introduction

Significant quantities of biowastes are generated and accumulated in the natural environment due to the rapid growth of population and increasing consumption of products (Maina et al., 2017). Sources of biowasts mainly include municipal solid wastes, agricultural wastes, animal manure and biosolids from wastewater treatment plants. The rise of biowastes generation creates a number of challenges for biowaste management around the world, and therefore causes risks for the environment and human health (Lebersorger & Beigl, 2011). The traditional techniques for biowaste management like burning, landfilling, composting and anaerobic digestion all have their own drawbacks for the environmental sustainability. Therefore, it is significant to provide a more sustainable strategy for biowastes management.

The increasing demands for products and services caused by population growth result in an increase in the utilization of fossil fuels and resources, which in turn contribute to climate change and resource depletion (Elkhalifa et al., 2019). The reutilization of biowastes as feedstocks for the production of valuable products and bioenergy is a sustainable solution for the management of biowastes, and mitigation of climate change and resource depletion (Li et al., 2019a; Navia & Crowley, 2010; Qambrani et al., 2017). Biological and thermochemical technologies are mainly used for the conversion of biowastes to valuable products (Lohri et al., 2017). In the biological process, organisms are used to convert organic biomass to bioenergy while in the thermochemical conversion technique heat and the chemical catalysts are used to produce energy (Awasthi et al., 2021a; Tripathi et al., 2016). Biological conversion such as anaerobic digestion of the biowastes results in methane generation, while thermochemical techniques like pyrolysis and gasification leads to three products including bio-oil, biochar and gases (Awasthi et al., 2021b; Bhatia et al., 2018). One of the major drawbacks of biological process is the slow and uncompleted conversion of biowastes into the energy and treatment of hazardous contaminants efficiently (Bhaskar et al., 2011). This limitation of the biological technology has make researchers turn to the study on thermochemical technologies.

Large availability of biowaste resources around the world gives a great potential for biochar production sustainably. Biochar production from biowastes through thermochemical technologies has been considered as a sustainable strategy for biowastes management (Owsianiak et al., 2021). Bio-oil produced in the pyrolysis process has a good feed stock for power generation as it contains high energy which is in some cases comparable to the fossil fuels after up-gradation (Park et al., 2008). Biochar with specific surface structure and high carbon content makes it useful for industrial applications. For example, the applications of the biochars to soil is helpful to improve the soil quality by increasing the retention of water and nutrients, as well as control the climate change by increasing the rate of carbon separation in soil (Sohi et al., 2010). Biochar also can be used in purification of water and wastewater to remove various pollutants like heavy metals and organic micropollutants (Xiang et al., 2020). In power generation biochar can be used as a fuel because biochar contains a high carbon percentage in it which can be used as fuel.

The biocahr production reduces the accumulation of wastes and solve challenges of wastes management in a sustainable approach due to the lesser energy consumption for the convertion to biochar and secondary use of biochar in the environment. Therefore, this chapter exhibits reuse of various biowastes as feedstocks for biochar production sustainably in biowaste management while focusing on the environmental benefits of this strategic.

2. Sources and management of biowastes

2.1 Municipal solid waste (MSW)

The quantity of municipal solid waste (MSW) is increasing due to urbanization, industrialization, and growth of population (Zhang et al., 2010). Globally, the annual generation of MSW has exceeded 1.3 billion tonnes and is expected to increase by 2.59 billion tonnes in 2030 and 3.4 billion tonnes by 2050 (Hoornweg & Bhada-Tata, 2012). The top three countries of MSW production are USA, China and India, with the value of 258, 220 and 169 million metric tons, respectively (Nanda & Berruti, 2020). The composition of the MSW includes food waste, wood and yard trimmings, paper, cotton, glass, metals, leather, plastics and others (Cheng & Hu, 2010). As shown in Table 1, biowastes including biodegradable garden and park waste, as well as food wastes represent a significant component of MSW, which account for 30–45 wt% of this total depending on the country and region, and up to 40–70 wt% of MSW in developing countries (Abdel-Shafy & Mansour, 2018). In China, the food waste occupied the highest proportion in MSW, which is up to 60% (Zhang et al., 2010). Food wastes are generated in abundance around the world because of the vast tonnages. It has been estimated that one-third of the edible parts of food produced for human consumption is lost or wasted globally, reaching 1.3 billion tons per year (Elkhalifa et al., 2019).

Inset Table 1

Strategies for the management of MSW mainly include recycling, thermal treatment, composting or landfilling (Nanda & Berruti, 2020). Landfilling or open dumping is the most common strategy of MSW management globally (Kumar & Samadder, 2017). Nanda and Berruti (2020) stated that for MSW collected by the municipalities, around 70% is landfilled or dumped, 19% is recycled and 11% is used for energy recovery. However, landfilling or open dumping is one of the major contributor of greenhouse gases (GHG) emissions from organic waste degradation in landfills, which leads to the climate change (Sridevi et al., 2012). Leachates of landfill contain toxic elements, persistence organic pollutants, and heavy metals pose huge threats to the environmental safety and human health, and it is difficult to deal with (Gunarathne et al., 2019). Hence, it is significant to develop environmentally friendly approach to reduce hazardous effects of contaminants from MSW (Wijesekara et al., 2014).

Driving by the shortage of global energy and resources, it is time to realize that MSW is a valuable resource that can be converted to sustainable energy and value-added products in an economical and environmentally friendly way (Kumar & Samadder, 2017). Biological and thermochemical and conversion are promising technologies to convert MSW into solid, liquid and gaseous fuels, thereby reutilizing for secondary usage (see Fig.1). The biological technology including anaerobic digestion or composting has been considered as sustainable approaches for MSW management that reduces GHG production from landfilling and produces soil amendment products to improve soil quality (Galgani et al., 2014). However, the treatment effectiveness is unstable and requires a long reaction time. Emissions of other GHG, odorous or toxic gases also can affect net climate and air quality impacts (Preble et al., 2020). Additionally, heavy metals or other toxic compounds concentrations may increase in soil and food products cultivated in soil amended with SWS compost or solid digestate (Wei et al., 2017). Thermal conversion such as incineration, pyrolysis and gasification, which can convert MSW into energy, fuel oil or gas. Combustion and gasification are performed in the presence of oxygen and partial oxygen, respectively, while pyrolysis is performed in the absence of oxygen. The main differences among these three thermal treatment processes are the presence of oxygen and the operating temperature, which determine the quality and type of the products (Kumar & Samadder, 2017). Incineration, which is a controlled combustion of wastes at high temperature, is mainly suitable for non-biodegradable wastes or MSW with less moisture content (Shi et al., 2016). Although incineration can reduce about 90% MSW volume, the high cost and moisture of the waste limit its wide application, due to the generally large quantity and high moisture content of MSW (Alam & Qiao, 2020).

Inset Fig. 1

Comparatively, pyrolysis is a sustainable MSW treatment technology, which also can cause a drastic reduction of the MSW volume by converting them into biochar but requiring lesser energy. The production of biochar from kinds of MSW in different pyrolysis reactors under various process conditions have been comprehensively reviewed by other researchers (2019) and. The advantages of using pyrolysis of biowaste for the production of value-added products, especially biochars, have been demonstrated in a number of recent applications. Specifically, the biochar derived from MSW has a high range of properties, which can be further be utilized as a soil amendment for soil quality improvement, nutrient recovery, carbon sequestration and climate-change mitigation, as well as an adsorbent for wastewater purification (Gunarathne et al., 2019; Xiong et al., 2019).

2.2 Agricultural residuals

Agriculture is a major resource for improving the standard of living of world's population, which has increased more than three times over the last 50 years to guarantee the adequate nutrition and health of people worldwide (Duque-Acevedo et al., 2020). It is reported that around 23.7 million tons of food is produced per day in Agriculture sectors worldwide (Duque-Acevedo et al., 2020). Large amounts of agricultural residues, such as corn stover, wheat straw, and rice straw are generated as a byproduct during the harvesting agricultural crops (Tripathi et al., 2019). Some agricultural wastes and their corresponding characteristics have been displayed in Table 2 (Ioannidou & Zabaniotou, 2007). As observed in Table 2, these field residues are carbon-based materials, low in nitrogen and vary with geographical location. These agricultural wastes are burgeoning problems, as their disposal and management are not efficient or universally applied.

Inset Table 2

Although a small proportion of agricultural residues is occasionally used as fertilizer or livestock feed, most of these residues are left in the field and burned in the open to get rid of the huge volumes of these wastes before next crop season coming (Mohammed et al., 2018). Burning of agricultural residues in the field is one of the major contributors of air pollution on local, regional and global scale (Ravindra et al., 2019). Carbon, nitrogen and sulphur in crop residues are completely burnt and lost to the atmosphere in the process of burning, leading to emissions of various pollutants to the atmosphere, such as particulate matter (PM10, PM2.5), carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), oxides of nitrogen (NOx), Ammonia (NH_3), Methane (CH_4), Elemental Carbon (EC), Organic Carbon (OC), Volatile Organic Compounds (VOCs), Polycyclic Aromatic Hydrocarbons (PAHs) (Lohan et al., 2018). These emissions result in global warming and a serious threat to the human health (Ravindra et al., 2019). It is estimated that open burning produces about 40 Mt CO_2 equivalent (Billa et al., 2019). Moreover, the burning of crop residue has an adverse effect on soil quality by destroying the existing minerals present in the soil (Kumar & Joshi, 2013).

The increase of agricultural production due to the global population growth will lead to continuous generation of agricultural residues. In addition to environmental pollution, the economic losses caused by burning of these residues should not be overlooked. Agricultural residues constitute a large biomass resource, which are an important feedstock for bioenergy production. Hence, it is necessary to identify sustainable technologies for the conversion of agricultural residues to value-added products. Compositions of agricultural residues are mainly cellulose, hemicellulose, and lignin (Bentsen et al., 2014).

Similar with the MSW, technologies for the conversion of agricultural residues into valuable substance also have been classified into biological and thermochemical terms (Pattanaik et al., 2019). The main biological conversion technologies can be divided into anaerobic digestion and fermentation, while the main thermochemical technologies can be grouped into combustion, gasification, and pyrolysis. The study by Simonyan and Fasina (2013) indicated that the biological conversion only can degrade the cellulose and hemicellulose part, but the lignin fraction can be converted to bioenergy using a thermochemical conversion method.

From the perspective of sustainable development, the use of available biomass resources to meet the needs of communities is essential for ecological sustainability. It is strongly recommended that smallholders can use pyrolysis to convert local agricultural residues into biochar and then apply to agricultural land to improve soil fertility and crop productivity. For example, research by Speratti et al. (2018) indicated that transforming local agricultural residues readily available into biochar can thus contribute to the improvement of soil quality and plant growth in a Cerrado region (Brazil) Arenosol, providing an alternative form of waste disposal for these residual materials. This conversion can achieve the goal of “closing the loop” in agriculture. The conversion of agricultural wastes into biochar is also a sustainable strategy towards climate change mitigation and circular bioeconomy (Darley et al., 1966). The GHG and toxic emissions from decomposition and burning of agricultural residues can be decreased by the storage of carbon in biochar for a significantly long period, and the production of other carbon products (bio-oil and syngas). It is reported that the proportion of carbon sequestration is about 50% by biochar production, only 3% by burning, and less than 20% by biological decomposition (Zhang et al., 2016). Zabaniotou (2014) indicated that the biochar production from waste materials in rural area could provide waste management solutions with economic, social, and environmental outcomes in the circular economy. This strategy boosts sustainable regional development and self-sufficient energy production, improves the living conditions of rural communities and increases the income of farmers.

2.3 Animal manure

Animals, such as dairy, beef, swine, poultry and companion animals, are raised for food and non-food purposes around the world (Romney et al., 1994). Animal manures are inevitable wastes generated during the process of animal. Typically, manure includes feces, urine, bedding, wasted feed, water (drinking and wash), hair, and soil. Animal manures containing high levels of nutrients for plant growth can used as fertilizer in soils (Bushell, 2018). However, if the application rate is higher than the expected nutrient requirements of the crop, phosphorus and nitrogen will accumulate in the soil (Bushell, 2018). The erosion of surplus nitrogen and phosphorous by surface runoff and cause eutrophication of water bodies (Loyon, 2018). Moreover, animal manure contains high levels of toxic pollutants and pathogens (*Escherichia coli, Clostridium, Salmonella* spp.*, Listeria monocytogenes* and *Campylobacter*) is also a threat to humans and animals (Kumar Awasthi et al., 2019).

Large amounts of micro-organisms in animal manure also make it a source of major risk to the public. In fact, several foodborne diseases around the world are directly or indirectly related to manure contamination. Therefore, sustainable manure management technologies are advocated to address the environmental issues of animal manures, which have a lot of benefits to the society. Technologies for manure management, including aerobic, anaerobic, and thermochemical processes, have been extensively reported previously (Awasthi et al., 2019). Anaerobic digestion and composting have been considered as effective methods for the pretreatment of manures prior to land application to reduce the burden of pathogens and antibiotics, as well as some some antibiotic resistance genes (ARGs) (Khoshnevisan et al., 2021). However, it is difficult to remove heavy metals, antibiotics and hormones through biodegradation. Some ARGs could still exist and even be enriched after the biological treatment (Gurmessa et al., 2020; Riaz et al., 2020).

Alternatively, the conversion of animal manure to biochar via pyrolysis technology could remove antibiotics, immobilize heavy metals, kill pathogenic bacteria and produce high-quality biochar simultaneously (Méndez et al., 2014; Tian et al., 2019). Tian et al. (2019) concluded that tylosin, tetracycline and sulfonamide antibiotics in livestock manure were completely removed at by pyrolysis 600 °C. Higher temperatures (above 600 °C) was favourable for the immobilization of heavy metals in the manure. The study by Zeng et al. (2018) also found that heavy metals in swine and goat manure could be successfully immobilized after pyrolysis. Devi and Saroha (2014) and Wang et al. (2016) evaluated the fractionation, bioavailability, leachability and ecotoxicity of heavy metals in biochar obtained from sludge and observed that all heavy metals were immobilized in the biochar after pyrolysis, but the bioavailability, and eco-toxicity and leaching potential of the heavy metals were decreased. Hence, it is more environmentally friendly and safer and more for apply the biochar in soil than the raw animal manure and sewage sludge.

The biochar produced from animal manure with high concentrations of nutrients is a promising alternative to synthetic fertilizers, and has been suggested as promising solutions for addressing the above mentioned environmental issues. Biochar not only can retain nutrients in the soil but also can release nitrogen, phosphorus, and potassium for the growth of plants (Biederman & Harpole, 2013). The surface characteristic of biochar enables it to adsorb heavy metals and antibiotics, thereby, reducing their accumulation in soil, their uptake by plants and subsequent intake by humans and animals (Hayyat et al., 2016). The study by Zhou et al. (2019) indicated that the dissemination of ARGs from animal waste to the environment can be effectively mitigated by converting manure into biochar.

2.4 Biosolid

Biosolids are treated sewage sludge from wastewater treatment plants. Increasing volumes of biosolids are being produced as a result of population growth and the implication of new wastewater plants (Arulrajah et al., 2011). The total biosolids production of Australia increased year by year, which was about 371,000 dry tonnes in 2019, 329,000 dry tonnes in 2017, and 310,000 dry tonnes in 2015 (ANZBP, 2019). The chemical composition and properties of biosolids depend on treatment technology and retention time in the wastewater facilities (Paz-Ferreiro et al., 2018). Typically, biosolids are composed of organic (more than 50% of the dry matter) and inorganic materials. The organic matter in biosolids can improve soil structure or reduce the possibility of surface runoff and erosion. The mineralization of organic matter can release macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) and micronutrients (copper, zinc, iron, boron, molybdenum and manganese) to meet the demand of crop growth (Hernández-Apaolaza & Guerrero, 2008). Therefore, the biosolids have been applied in agricultural land to increase the soil quality. The proportion of biosolids to agricultural is about 70% in Australia and 51% in the United States (Patel et al., 2020). However, heavy metals, poorly biodegradable trace organic compounds and pathogenic organisms accumulated in biosolids during wastewater treatment cause a major concern for the land application of biosolids in recent years. After soil application, these toxic contaminants can enter the environment via leaching and surface runoff (Kumar & Joshi, 2013). Additionally, the uptake of these pollutants by crops might pose risks to human health and possibly cause pollution to the food-supply chain (Agrafioti et al., 2013).

Fig. 2 displays different strategies for the management of biosolids (Agrafioti et al., 2013). Current strategies for the treatment of biosolids such as incineration and landfilling have some drawbacks. For instance, the incineration of biosolids can largely reduce the volume of biosolids and lead to the thermal breakdown of pathogens and trace contaminants in biosolids, but it is restricted by many countries becuae it may emit harmful substances including acid gases, dioxins, particulate matter and NOx to cause air pollution. Similar with other types of wastes, landfilling was a low-cost option for managing biosolids in the past, it is also becoming increasingly restricted in different countries. The high amount of organic matter present in the biosolids contributes to methane emissions from landfills and to leachate (Patel et al., 2020). Hence, landfilling and incineration of biosolids are no longer acceptable under the current climate change scenario.

Inset Fig. 2

Alternatively, the transformation of biosolids to biochar via pyrolysis is attracting great interest for biosolids management recently (Fonts et al., 2012). The biochar production process not only can reduce the volume of biosolids, but also can destruct pollutants like emerging micropollutants and heavy metals in the char matrix while having minimal environmental impacts. Meanwhile, biochar derived from biosolids possesses high amounts of carbon and nutrients, and a significant cation exchange capacity (Paz-Ferreiro et al., 2018).

3. Technologies for sustainable biochar production from biowastes

Main aspects that should be considered in technologies for sustainable biochar production are improving energy efficiency, reducing pollution emissions, recovering valuable products to improve process economics, controlling operating conditions to modify yields and characteristics of products, and the flexibility of raw materials (Rosas et al., 2015). Thermochemical conversion technologies for biochar production including pyrolysis and gasification serve as a sustainable strategy for biowastes management (You & Wang, 2019). According to previous studies on the cost analysis of various technologies for the generation of biochar and bio-oil from various biowastes, slow pyrolysis can produce higher yields of biochar (around 35%) with higher stability and carbon content(>55%) in comparison to fast pyrolysis and gasification (Mohammadi et al., 2017a; Rosas et al., 2015). Slow pyrolysis occurs in the absence of oxygen at a temperature of 300 to 700 °C, with the production of biochar, bio-oil, and syngas. The percentage of these products depend on the temperature, residence time and heating rate of the process (Kumar et al., 2020). Bio-oil and syngas can be used as fuels to generate heat and/or electricity or upgraded to value-added chemicals (e.g., transportation liquid fuel and hydrogen) (Hansen et al., 2020). Pyrolysis-based biochar production plants have been developed by using various types of biowastes (e.g., cotton stalk, rice husk, forestry residue, wheat straw, and rape stalk) as feedstocks with a capacity ranging from 365 tonnes/year to 48400 tonnes/year. The yield of biochar production in these plants ranges from 80.3 to 11400 tonnes/year. The amounts of syngas, wood tar, and wood vinegar are $1.8 \times 10^4 - 1.58 \times 10^7$ m^3/year, $2.92 - 1920$ tonnes/year and $36.5 - 9520$ tonnes/year, respectively (Ok et al., 2018).

It is important for the biochar production technology to provide both ecological and economic benefits to make its application more sustainable. Hence, the energy efficiency of a biochar production technology is a key factor in the selection of a biochar system (Nsamba et al., 2015). Actually, the fuel gas and bio-oil generated during the pyrolysis process can be used for the pyrolysis reaction. The amount of biofuel consumed for the pyrolysis process mainly depends on the pyrolysis temperature and the biochar product specification, which is in the range of 10-25% of the produced biofuel. Elkhalifa et al. (2019) indicated that a self-sustainable process could be achieved via using the generated heat during biochar production in a mobile and self-sustainable demonstration scale pyrolysis reactor. The energy content in the products (5.52 MJ/kgfeedstock) still had surplus energy (about 2.73 MJ/kgfeedstock) after meeting the energy requirements of the process (Rosas et al., 2015).

Feedstock collection, transport, and pretreatment are major contributors to the low efficiencies and high costs of the biochar production systems (Wang et al., 2012). Mobile systems or distributed biochar production systems have been considered as promising solutions to reduce the collection and transportation costs of feedstocks by utilizing locally generated biowastes and catering for the bioenergy and biochar demands of local rural communities (You et al., 2020). Using a mobile reactor, the transportation of feedstock is nearly non-existent, thus reducing CO_2 emissions associated to transport and external energy demand. Moreover, the development of distributed biochar production systems through using the local biomass wastes not only can avoid the transportation cost, but also can create business and employment in rural area (Fytili & Zabaniotou, 2018).

Techno-economic and environmental impact assessments are conducted for the conversion of manure to biochar on-site using a portable refinery unit on a real case study in Twin Falls, Idaho, USA (Struhs et al., 2020). The results showed that converting cattle manure to biochar near the collection sites can reduce the biochar production cost and manure environmental impacts, thereby enhancing sustainable benefits of the entire manure-to-biochar supply chains and stimulating the biochar industry. Therefore, it is necessary to conduct more studies to design and manufacture mobile and self-sustained pyrolysis reactors for biochar production to meet the requirements of sustainable biochar production.

4. Environmental benefits of biochar production from biowaste

Life cycle assessment (LCA) have been used by several studies to evaluate biochar production by pyrolysis technology in different countries (e.g., Spain, Brazil, and USA) (Mohammadi et al., 2017b). Most studies are focused on calculating potential benefits of biochar from a GHG pespective, which is the most environmental benefit of biochar production and application (Matuštík et al., 2020). For instance, a prospective LCA was used to assess the climate impact of large-scale biochar production in Stockholm (Azzi et al., 2019). Through evaluating the potential of using the heat and power from pyrolysis of woodchips for the city of Stockholm, and using biochar as a feed and manure additive on Swedish dairy farms, it is concluded that building a new pyrolysis plant becomes a better climate option than conventional combustion. El Hanandeh (2013) used LCA to analyse the reduction of carbon emission potential of utilizing olive husk as the raw material for biochar production in a mobile pyrolysis system in four scenarios, and resulted that all scenarios had a significant reduction in carbon emission. A case study by Huang et al. (2015) indicated that the production of biochar from poultry litter with heat and power generation was technically and economically feasible based on a pyrolysis/gasification process, which offers a significant CO_2 saving opportunity due to the low CO_2 emissions on the basis of heat generation and biochar carbon sequestration in soils (Lehmann et al., 2006). Carbon sequestration via biochar has been considered a negative emission method for carbon management due to its capacity to lock black carbon in the soil, which will remain there for multiple centuries (Belmonte et al., 2018). Lee et al. (2010) reported that the maximum storage capacity of biochar carbon in agricultural soils (1411 million hectares) has been estimated to be approximately 428 GtC in the world. Through LCA, it is proved that higher ash content of the feedstocks, the higher biochar yield, which leads to in a larger reduction of GHG emissions (Li et al., 2019b).

In addition to the reduction of GHG emissions, other environmental and economic benefits of biochar also have been stated. Biochar produced from nutrient-rich biowastes can improve soil fertility and crop productivity significantly, as well as reduce the leaching of pollutant such as nutrients, heavy metals, and pesticides, to the aquatic environment (Uchimiya et al., 2010). Characteristics of biochars produced from different biowastes have been given in Table 3 (Ahmad et al., 2014). Considering the capacity of biochar to retain nutrients in the soil and release macronutrients, the need of soil for fertilizer can be reduced. Moreover, the water-holding and adsorption capacity and of biochar can enhance crop yield and reduce the uptake of heavy metals by plants (Struhs et al., 2020).

Inset Table 3

Biochar as adsorbent also has high potential in the treatment of water and wastewater, in terms of removing heavy metals and organic micro-pollutants such as pharmaceuticals, antibiotics, and pesticides from aquatic environment to improve the quality of drinking water (Huggins et al., 2016; Thompson et al., 2016; Tran et al., 2020). Biochar can be used as an alternative product to activated carbon in wstewater treatment. A review paper from a lifecycle perspective of the use of biochar adsorption matrix indicated that the environmental impact of biochar showed more sustainable profiles than the use of activated carbon as conventional adsorption material (Moreira et al., 2017).

5. Conclusions and perspectives

This chapter presents the sources, production and management of different kinds of biowastes, including municipal solid waste, agricultural residues, animal manure and biosolids. Without proper management, increasing production of these wastes will cause pollution problems and threaten human health and environmental safety. It is significant to develop sustainable and low-cost biowastes management technologies. Biochar production through slow pyrolysis is an environmental friendly alternative treatment method of biowaste when compared to conventional management strategies, biological technologies and other thermochemical technologies. Despite mobile and self-sustainable systems have been considered as economical and environmentally friendly technologies for sustainable biochar production, there are very few commercially operating systems for treating biowastes. Therefore, more research about the appropriate design, operation and techno-economical assessment of the system are required for the further practical implication. It is necessary to develop a mobile but economical system in the future that can easily be adopted into the local community for sustainable biochar production.

Biochar produced from various biowastes can further bring lots of benefits to the environment. High carbon content of biochar shows its benefit to reduce GHG emissions, and this has been reflected through the life cycle assessment of biochar application as soil amendment. Biochar with specific properties and contains essential plant nutrients could be used as soil amendment to improve the quality of some soils and increase plant growth. The biochar is also a promising alternative to activated carbon for removing heavy metals and organic micro-pollutants from water and wastewater. Hence, converting biowastes to biochar is strongly recommended for biowastes management, which contributes to the environmental sustainability. Whereas, there are still some challenges for the future application of biochar which can be explored as part of future research. Currently, a majority of studies focused on the role of biochar in agricultural productivity, climate change and wastewater treatment, but there is still lack of research on how a specific biochar production technology affects characteristics, environmental impacts and production cost of biochar. It is also important to identify the optimum feedstock (e.g. single or mixed kind of biowastes) and production condition for the production of specific biochar with specific applications (e.g. soil amendment and wastewater purification).

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Table captions

Table 1 Major composition of municipal solid waste;

Table 2 Examples of agricultural residues and their corresponding characteristics;

Table 3 Characteristics of biochars produced from different biowastes.

Figure captions

Fig. 1 Technologies for municipal solid waste treatment and their products;

Fig. 2 Different strategies for biosolids management.

Table 1 Major composition of municipal solid waste (Kumar & Samadder, 2017).

Component	Material	Percentage (%)
Kitchen/yard waste	Food waste (e.g., food and vegetable refuse, fruit peels, corncob), yard waste (e.g., leaves, grass, tree trimmings), etc.	30–45
Paper/cardboard	Paper bags, cardboard, corrugated board, box board, newsprint, magazines, tissue, office paper, and mixed paper, etc.	25
Plastic	High-valued plastics, polypropylene bottles, beverage bottles, low-valued plastics (Polythene plastic bags, polystyrene plastic packages such as mess tins made from flexible plastics and plastic cup for yoghurt, ice-cream, etc.) and others.	13.2
Metals & glass	Ferrous (e.g., food cans, etc.), non-ferrous (e.g., aluminium cans, foil, ware, and bimetal, etc.), wire, fence, knives, bottle covers, etc., and bottles, glassware, light bulbs, ceramics, etc.	9.4

Table 2 Examples of agricultural residues and their corresponding characteristics (Ioannidou & Zabaniotou, 2007).

Agricultural residuaes	**Moisture %ww**	**Ash %ww**	**Volatiles %ww**	**C % ww**	**H % ww**	**O % ww**	**N % ww**	**S % ww**	**HHV kcal/kg**
Olive tree prunings	7.1	4.75	n.a	49.9	6	43.4	0.7		4500
Cotton stalks	6	13.3	n.a	41.23	5.03	34	2.63	0	3772
Durum wheat straw	40	n.a	n.a	n.a	n.a	n.a	n.a	n.a	4278
Corn stalks	0	6.4	n.a	45.53	6.15	41.11	0.78	0.13	4253
Soft wheat straw	15	13.7	69.8	n.a	n.a	n.a	n.a	n.a	4278
Vineyward prunings	40	3.8	n.a	47.6	5.6	41.1	1.8	0.08	4011
Corn cobs	7.1	5.34	n.a	46.3	5.6	42.19	0.57	0	4300
Sugar beet leaves	75	4.8	n.a	44.5	5.9	42.8	1.84	0.13	4230
Barley straw	15	4.9	n.a	46.8	5.53	41.9	0.41	0.06	4489
Rice straw	25	13.4	69.3	41.8	4.63	36.6	0.7	0.08	2900
Peach tree prunings	40	1	79.1	53	5.9	39.1	0.32	0.05	4500
Almond tree prunings	40	n.a	n.a	n.a	n.a	n.a	n.a	n.a	4398
Oats straw	15	4.9	n.a	46	5.91	43.5	1.13	0.015	4321
Sunflower straw	40	3	n.a	52.9	6.58	35.9	1.38	0.15	4971
Cherry tree prunings	40	1	84.2	n.a	n.a	n.a	n.a	n.a	5198
Apricot tree prunings	40	0.2	80.4	51.4	6.29	41.2	0.8	0.1	4971

Table 3 Characteristics of biochars produced from different biowastes (Ahmad et al., 2014).

Feedstock	**Pyrolysis temperature (°C)**	**Heating rate (°C /min)**	**Yield (%)**	**Mobile matter (%)**	**Fixed matter (%)**	**Ash (%)**	**pH**	**C (%)**	**H (%)**	**O (%)**	**N (%)**	**Surface area ($m^2 g^{-1}$)**	**Pore volume ($cm^3 g^{-1}$)**
Broiler litter	350	–	–	–	–	–	–	45.6	4	18.3	4.5	60	0
Broiler litter	700	–	–	–	–	–	–	46	1.42	7.4	2.82	94	0.018
Buffalo weed	300	7	50	44.2	30.4	20.4	8.7	78.09	4.26	7.44	10.21	4	0.01
Buffalo weed	700	7	29	20.9	46.8	32.3	12.3	84.96	1.09	6.56	7.4	9.3	0.02
Canola straw	400	20	27.4	–	–	–	–	45.7	–	–	0.19	–	–
Chicken litter	620	13	43–49	16	30.8	53.2	–	41.5	1.2	0.7	2.77	–	–
Corn cobs	500	–	18.9	–	–	13.3	7.8	77.6	3.05	5.11	0.85	0	–
Corn stover	450	–	15	12.7	28.7	58	–	33.2	1.4	8.6	0.81	12	–
Corn stover	500	–	17	–	–	32.8	7.2	57.29	2.86	5.45	1.47	3.1	–
Cottonseed hull	200	–	83.4	69.3	22.3	3.1	–	51.9	6	40.5	0.6	–	–
Cottonseed hull	350	–	36.8	34.9	52.6	5.7	–	77	4.53	15.7	1.9	4.7	–
Cottonseed hull	500	–	28.9	18.6	67	7.9	–	87.5	2.82	7.6	1.5	0	–
Cottonseed hull	650	–	25.4	13.3	70.3	8.3	–	91	1.26	5.9	1.6	34	–
Cottonseed hull	800	–	24.2	11.4	69.5	9.2	–	90	0.6	7	1.9	322	–
Feed lot	350	2.5	51.1	47.9	23.5	28.7	9.1	53.32	4.05	15.7	3.64	1.3	–
Feed lot	700	8.3	32.2	19.8	36.3	44	10.3	52.41	0.91	7.2	1.7	145.2	–

Fescue straw	100	–	99.9	69.6	23.5	6.9	–	48.6	7.25	44.1	0.64	1.8	–
Fescue straw	200	–	96.9	70.7	23.6	5.7	–	47.2	7.11	45.1	0.61	3.3	–
Fescue straw	300	–	75.8	54.4	36.2	9.4	–	59.7	6.64	32.7	1.02	4.5	–
Fescue straw	400	–	37.2	26.8	56.9	16.3	–	77.3	4.7	16.7	1.24	8.7	–
Fescue straw	500	–	31.4	20.3	64.3	15.4	–	82.2	3.32	13.4	1.09	50	–
Fescue straw	600	–	29.8	13.5	67.6	18.9	–	89	2.47	7.6	0.99	75	–
Fescue straw	700	–	28.8	9.1	71.6	19.3	–	94.2	1.53	3.6	0.7	139	–
Oak bark	450	–	–	22.8	64.5	11.1	–	71.25	2.63	12.99	0.46	1.9	1.06
Oak wood	400–450	–	–	15.6	78.3	2.9	–	82.83	2.7	8.05	0.31	2.7	0.41
Orange peel	150	–	82.4	–	–	0.5	–	50.6	6.2	41	1.75	22.8	0.023
Orange peel	200	–	61.6	–	–	0.3	–	57.9	5.53	34.4	1.88	7.8	0.01
Orange peel	250	–	48.3	–	–	1.1	–	65.1	5.12	26.5	2.22	33.3	0.02
Orange peel	300	–	37.2	–	–	1.6	–	69.3	4.51	22.2	2.36	32.3	0.031
Orange peel	350	–	33	–	–	2	–	73.2	4.19	18.3	2.3	51	0.01
Orange peel	400	–	30	–	–	2.1	–	71.7	3.48	20.8	1.92	34	0.01
Orange peel	500	–	26.9	–	–	4.3	–	71.4	2.25	20.3	1.83	42.4	0.019
Orange peel	600	–	26.7	–	–	4.1	–	77.8	1.97	14.4	1.8	7.8	0.008
Orange peel	700	–	22.2			2.8	–	71.6	1.76	22.2	1.72	201	0.035
Paper sludge	105	7	–	49.3	17	31.5	7.9	45.93	5.67	46.8	1.51	4.2	0.02

Paper sludge	300	7	65.8	16.6	30.4	51.2	7.8	60	3.71	33.81	2.49	4.3	0.02
Paper sludge	700	7	40.3	3.2	21.7	73.8	9.9	59.88	0.71	37.89	1.46	145.6	0.07
Peanut shell	300	7	36.9	60.5	37	1.2	7.8	68.27	3.85	25.89	1.91	3.1	–
Peanut shell	700	7	21.9	32.7	58.1	8.9	10.6	83.76	1.75	13.34	1.14	448.2	0.2
Peanut straw	400	20	28.2	–	–	–	–	42.9	–	–	1.5	–	–
Pine needles	100	–	91.2	–	–	1.1	–	50.87	6.15	42.27	0.71	0.7	–
Pine needles	200	–	75.3	–	–	0.9	–	57.1	5.71	36.31	0.88	6.2	–
Pine needles	250	–	56.1	–	–	1.2	–	61.24	5.54	32.36	0.86	9.5	–
Pine needles	300	–	48.6	–	–	1.9	–	68.87	4.31	25.74	1.08	19.9	–
Pine needles	400	–	30	–	–	2.3	–	77.85	2.95	18.04	1.16	112.4	0.044
Pine needles	500	–	26.1	–	–	2.8	–	81.67	2.26	14.96	1.11	236.4	0.095
Pine needles	600	–	20.4	–	–	2.8	–	85.36	1.85	11.81	0.98	206.7	0.076
Pine needles	700	–	14	–	–	2.2	–	86.51	1.28	11.08	1.13	490.8	0.186
Pine needles	300	7	57.6	38.6	54.2	7.2	6.4	84.19	4.37	7.57	3.88	4.1	–
Pine needles	500	7	31.8	15.8	72.4	11.8	8.1	90.1	2.06	3.74	4.1	13.1	0.015
Pine needles	700	7	25	6.2	75	18.7	10.6	93.67	0.62	2.07	3.64	390.5	0.12
Pine shaving	100	–	99.8	77.1	21.7	1.2	–	50.6	6.68	42.7	0.05	1.6	–
Pine shaving	200	–	95.9	77.1	21.4	1.5	–	50.9	6.95	42.2	0.04	2.3	–

Pine shaving	300	–	62.2	70.3	28.2	1.5	–	54.8	6.5	38.7	0.05	3	–
Pine shaving	400	–	35.3	36.4	62.2	1.1	–	74.1	4.95	20.9	0.06	28.7	–
Pine shaving	500	–	28.4	25.2	72.7	1.4	–	81.9	3.54	14.5	0.08	196	–
Pine shaving	600	–	23.9	11.1	85.2	3.7	–	89	2.99	8	0.06	392	–
Pine shaving	700	–	22	6.3	92	1.7	–	92.3	1.62	6	0.08	347	–
Pinewood	700	10	–	3.2	57.1	38.8	6.6	95.3	0.82	3.76	0.12	29	0.13
Poplar wood	400	8	32	–	–	3.5	9	67.3	4.42	–	0.78	3	–
Poplar wood	460	8	–	–	–	5.7	9.2	70	3.51	–	0.95	8.2	–
Poplar wood	525	8	–	–	–	6.8	8.7	77.9	2.66	–	1.07	55.7	–
Poultry litter	350	2.5	54.3	42.3	27	30.7	8.7	51.07	3.79	15.63	4.45	3.9	–
Poultry litter	700	8.3	36.7	18.3	35.5	46.2	10.3	45.91	1.98	10.53	2.07	50.9	–
Poultry manure	300	7	65.7	19	56.5	24	8.8	52.9	3.92	34.73	7.8	4.3	0.012
Poultry manure	400	7	54	8.2	63.8	28	10.6	51.04	3.15	39.35	5.41	11.6	0.027
Poultry manure	500	7	72	7.3	68.6	24	11	51.56	1.87	40.32	5.5	5.8	0.022
Poultry manure	600	7	47	5.4	71.6	22.6	11.5	52.28	1.44	40.27	4.24	3.7	0.019
Poultry manure	700	7	47	4.1	69.6	24.2	10.7	56.09	1.52	37.19	4.16	6.6	0.02
Rapeseed plant	400	5	39.4	27.1	60.7	12.2	–	71.34	3.93	10.84	1.43	16	1.244
Rapeseed plant	500	5	35.6	17.5	69.6	12.9	–	75.03	2.62	7.79	1.41	15.7	1.15

Rapeseed plant	600	5	32.2	11.5	74.7	13.9	–	78.48	1.88	3.94	1.53	17.6	1.263
Rapeseed plant	700	5	29.6	9	76.7	14.4	–	79.48	1.2	3.29	1.35	19.3	1.254
Rapeseed plant	800	5	28.2	6	79.7	15.3	–	79.51	0.72	2.61	1.45	19	1.155
Rapeseed plant	900	5	27.9	16.1	3.6	–	–	79.86	0.42	1.67	1.57	140.4	1.323
Rice husk	500	–	–	–	–	42.2	–	42.1	2.2	12.1	0.5	34.4	0.028
Saw dust	450	–	–	40.1	57.2	1.1	5.9	72	3.5	24.41	0.08	–	–
Saw dust	550	–	–	13.6	82.6	2.8	12.1	85	1	13.68	0.3	–	–
Sewage sludge	300	7	70.1	19.8	22.5	56.6	6.8	30.72	3.11	11.16	4.11	4.5	0.01
Sewage sludge	400	7	57.4	8.8	23.5	67.1	6.6	26.62	1.93	10.67	4.07	14.1	0.02
Sewage sludge	500	7	53.8	7.5	20	71.9	7.3	20.19	1.08	9.81	2.84	26.2	0.04
Sewage sludge	600	7	51.2	5.8	19.1	74.6	8.3	24.76	0.83	8.41	2.78	35.8	0.04
Sewage sludge	700	7	50.3	4.1	16.6	76.6	8.1	22.04	0.57	7.09	1.73	54.8	0.05
Soybean stover	300	7	37	46.3	38.8	10.4	7.3	68.81	4.29	24.99	1.88	5.6	–
Soybean stover	700	7	21.6	14.7	67.7	17.2	11.3	81.98	1.27	15.45	1.3	420.3	0.19
Soybean straw	400	20	24.7	–	–	–	–	44.1	–	–	2.38	–	–
Spruce wood	400	8	36	–	–	1.9	6.9	63.5	5.48	–	1.02	1.8	–
Spruce wood	460	8	–	–	–	3	8.7	79.6	3.32	–	1.24	14.2	–
Spruce wood	525	8	–	–	–	4.7	8.6	78.3	3.04	–	1.17	40.4	–
Swine solid	350	2.5	62.3	49.8	17.7	32.5	8.4	51.51	4.91	11.1	3.54	0.9	–

Swine solid	700	8.3	36.4	13.4	33.8	52.9	9.5	44.06	0.74	4.03	2.61	4.1	–
Swine solid	620	13	43–49	14.1	41.2	44.7	–	50.7	1.9	<0.01	3.26	–	–
Tire rubber	200	10	93.5	–	–	15	–	74.7	6.38	3.92	–	–	–
Tire rubber	400	10	59.3	–	–	15.4	–	77.7	3.56	3.34	–	24.2	0.08
Tire rubber	600	10	54.5	–	–	15.6	–	81.3	1.67	1.43	–	51.5	0.12
Tire rubber	800	10	43	–	–	10.5	–	86	0.87	2.16	0.47	50	0.11
Turkey litter	350	2.5	58.1	42.1	23.1	34.8	8	49.28	3.6	15.4	4.07	2.6	–
Turkey litter	700	8.3	39.9	20.8	29.2	49.9	9.9	44.77	0.91	5.8	1.94	66.7	–
Wheat straw	400	8	34	–	–	9.7	9.1	65.7	4.05	–	1.05	4.8	–
Wheat straw	460	8	–	–	–	12	8.7	72.4	3.15	–	1.07	2.8	–
Wheat straw	525	8	–	–	–	12.7	9.2	74.4	2.83	–	1.04	14.2	–

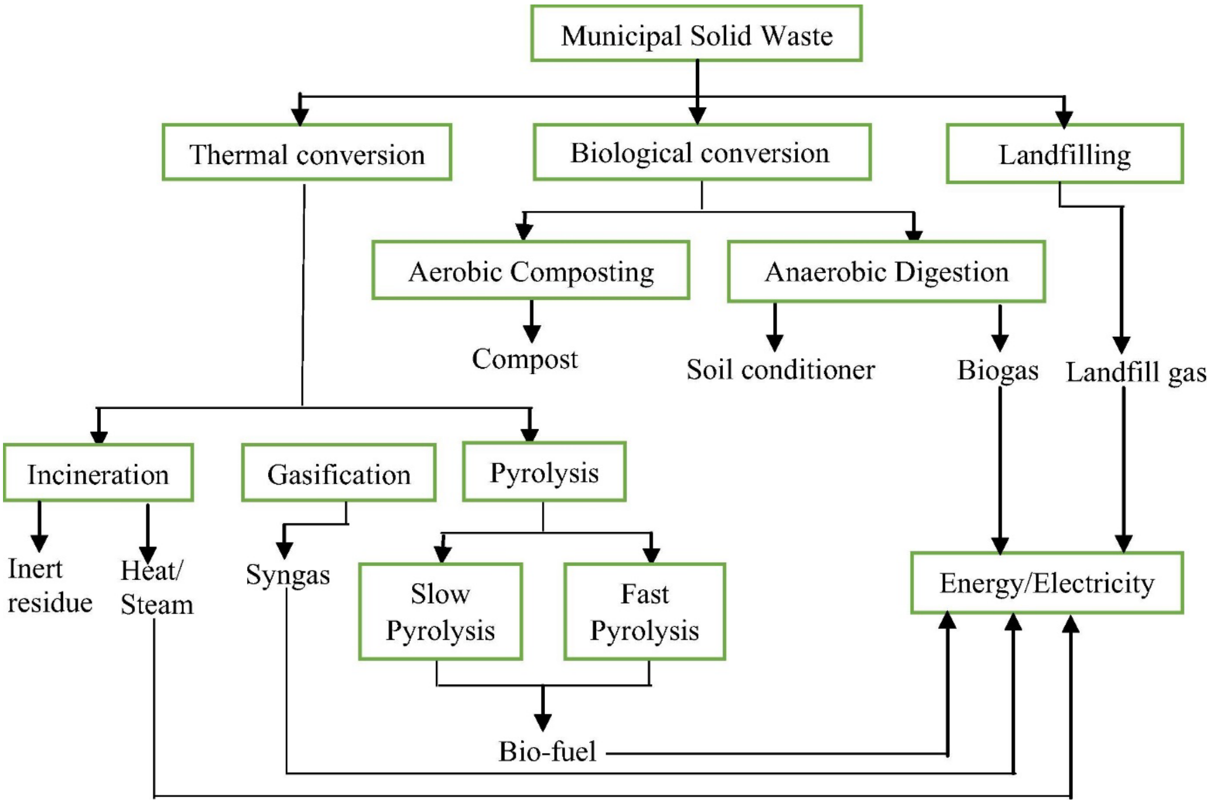

Fig.1 Technologies for municipal solid waste treatment and their products (Kumar & Samadder, 2017).

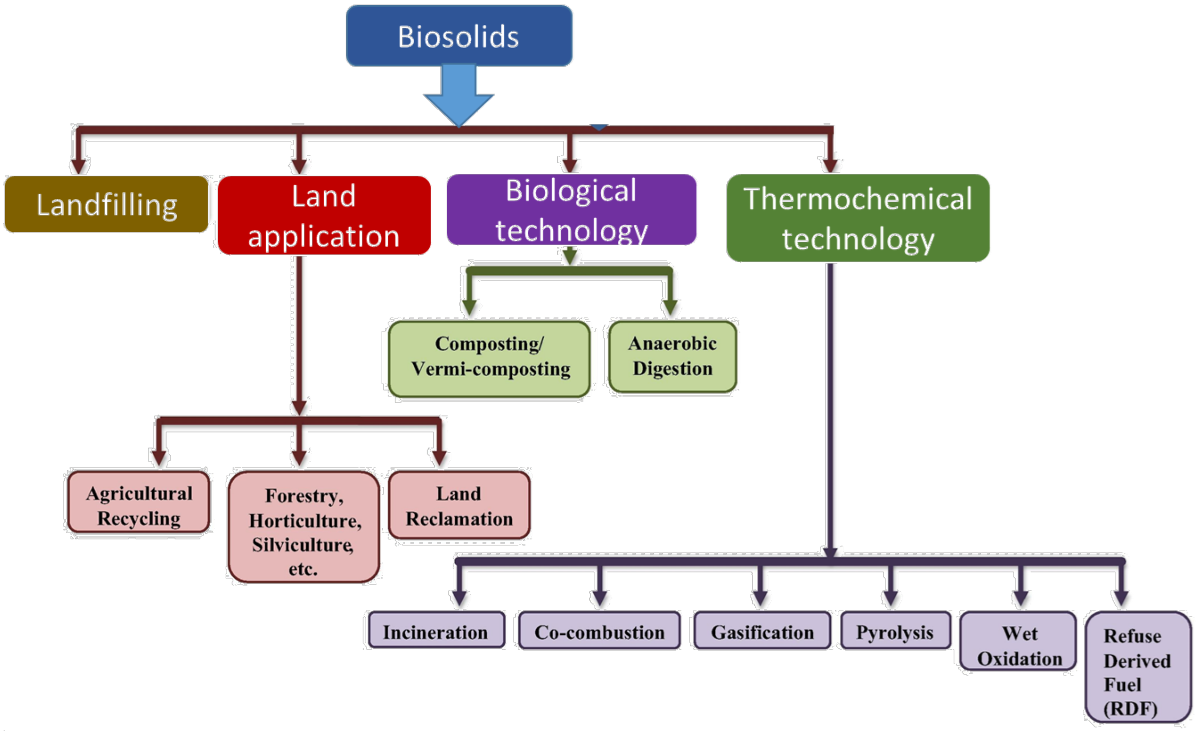

Fig. 2 Different strategies for biosolids management (Sharma et al., 2017).