Chapter 7
Municipal Waste Biochar for Energy and Pollution Remediation

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Contents

Abstract Municipal solid waste has become a hassle in many developing countries due to haphazard disposing to open dumpsites, which has zero management. This way of disposing the waste has negative impacts in the environment that can directly contribute to the climate changes and atmospheric pollution through greenhouse gas and volatile organic compound emission and water and soil pollution via landfill leachate as well. Biochar, a carbonaceous material produced by limited or no oxygen pyrolysis of biomass is an emerging efficient substitute for activated carbon. Its production utilizes different feedstock including municipal solid wastes, which is the "greener" approach of transforming the existing municipal waste into a value added product that can be used in contaminant mitigation and resource recovery by using it as an adsorbent and as a hybrid with soil for better plant growth. The long term benefits of these biochar additions to soil and water can be manifold and potential as an improved nutrient retention and availability to plant growth; this gives the impetus of having the "greener transformation" from municipal wastes to biochar. This chapter outlines the ways of production of biochar derived from municipal solid waste, its significance as an adsorbents and its promising potential in landfill cover, leachate treatment and for permeable reactive barriers.

7.1 Introduction

Handling of municipal solid waste creates problems than opportunities to produce valuable products such as energy, heat or recyclable material (Portugal-Pereira and Lee 2016). According to the assessment of World Bank, current worldwide generation of waste exceeds 1.3 billion tonnes per year and it is estimated to increase up to 2.2 billion tonnes per year by 2025 (Hoornweg and Bhada-Tata 2012). The rapid increase of municipal waste is a result of an exponential increase of population, industrialization and a migration of population from rural to urban areas due to economic development (de Souza Melaré et al. 2017). Municipal solid waste management is complex and is a mammoth task for municipalities due to the substantial demands of human and financial resources (Sequeira and Chandrashekar 2015b). Municipalities have to deal with significant quantities of organic and compostable wastes that are generated daily (Sequeira and Chandrashekar 2015a) to provide adequate and effective waste management to the community. Generally, municipal solid wastes can be categorized into organic and inorganic wastes

(Ghanimeh et al. 2012). Many different methods such as source reduction, recycling, composting, incineration and disposal into landfill have been practiced to manage solid waste worldwide. The World Bank and United States Agency for International Development (USAID) reports that 20–50% of the budget of a municipal council in developing countries is spent on solid waste management and these funds originate from less than 50% of an urban population (Henry et al. 2006; Memon 2010). This highlights the need for cost effective management of municipal waste. Management of pollutants in water bodies by using municipal waste derived biochar is one method of effectively using municipal solid waste, without disposing them into landfills. Hence, this chapter focuses on producing biochar from municipal solid wastes. Biochar is a soil enhancer, it can improve water quality by retaining nutrients, it enables sustainable management of organic solid waste and by retaining carbon it also helps combat climate change. These aspects are further detailed in the later parts of the chapter. The disposal methods of municipal wastes and environmental concerns that arise from these disposal methods are discussed in the next sections.

7.1.1 Disposal of Municipal Solid Wastes

In most countries, the disposal of municipal solid waste are done by incineration, sanitary landfill or open dumping even though, more environmental friendly low cost technologies such as composting and vermicomposting exist (Sequeira and Chandrashekar 2015b). With minimum consideration towards environmental impact, most developing countries dispose solid waste in open dumps (Vithanage et al. 2014; Wijesekara et al. 2014). Incineration is commonly applied on non-biodegradable wastes containing relatively a less moisture content and use of incineration reduce solid waste that goes into landfill (Tan et al. 2014). Incineration has several advantages over landfill disposal (Eriksson et al. 2007). An estimated 80–95% volume reduction of solid waste with incineration is a significant advantage to greatly reduce landfill and also to manage the leachate produce by landfill. This benefit is of greater significance for urban areas where land is scarce. Other advantages include opportunities to extract energy (as electricity and heat) and its ability to immobilize and decompose toxic constituents enabling the ash produced to be used in the construction industry (Huai et al. 2008).

Today economically developed countries consider municipal solid waste as a resource and aims to convert solid waste to energy (e.g. fuels, electricity and heat) (Antizar-Ladislao and Turrion-Gomez 2010; Guerrero et al. 2013) mostly using technologies such as pyrolysis and gasification (Liu and Liu 2005) and these technologies are detailed in the later parts of the chapter.

The disposal of solid waste is largely dependent on the composition of municipal solid waste, availability of resources such as funds, technical knowhow, availability of land and/or man-power. The composition and the quantity of municipal solid waste produced largely differs from country to country or region to region, the economic development of a county, the industrial structure, consumption patterns, culture, climatic factors and the types of energy sources used (Moya et al. 2017). For instance, low income economies tend to produce a great amount of organic wastes while high to middle economies tend to produce more inorganic waste (Trang et al. 2017). Trang et al. (2017), provides a comprehensive study of the household municipal waste of a city in Vietnam, and demonstrates a correlation between generation of solid waste and the socio-economic status of the household. Less solid wastes were generated by high income households compared to low income households.

7.1.2 Environmental Pollution

The rate of municipal solid waste production far exceeds its natural decomposition and as a consequence there are severe implications on the environment (Tan et al. 2015). As a consequence the negative aspects of municipal solid waste, specifically the solid waste in landfills has become a critical point of discussion due to the detrimental impacts caused on health and the environment (Palmiotto et al. 2014).

Many developing countries still use open dumping as the most common method of municipal solid waste disposal (Menikpura and Basnayake 2009; Mor et al. 2006). According to the Tränkler et al. (2005), most of the South and Southeast Asian countries use non-engineered landfills for solid waste disposal. The negative impacts these landfill sites have on the environment are non- reversible at times and causes permanent damage to natural resources that are at close vicinity of the landfill sites. Specifically, release of hazardous chemical compounds into nearby water bodies and ground water, the release of toxic fumes and emission of odor impacting the health and the quality of life of neighboring communities (Downey and Van Willigen 2005; Ariyawansha et al. 2011).

7.1.2.1 Gaseous Emission

Landfill gas emissions are a major pollutant of our atmosphere. The landfill gases are comprised mainly of methane, water vapors, carbon dioxide and small amounts of other organic compounds, which are categorized as non-methane organic compounds (Soltani-Ahmadi 2000). The non-methane organic compounds primarily are consisted of hazardous gaseous pollutants, odorous compounds and volatile organic compounds (Davoli et al. 2003; Fang et al. 2012). Generation of methane in landfills is due to a prolonged accumulation of organic solid wastes and this methane is able to trigger explosions, open fires and global warming (Sridevi et al. 2012). Compared to carbon dioxide, methane is roughly 30 times more potent as a heat-trapping gas, and hence has the potential to expedite global warming.

The production of odorous compounds in landfills is elevated especially in summer periods due to high temperatures (Dasgupta et al. 2013) and these odorous compounds affect human settlements in the vicinity. Benzene, Ethyl Benzene, Xylene and Toluene are major volatile organic compounds that are regularly found in landfill sites (Harkov et al. 1985; Jayawardhana et al. 2016). Long term exposure to even very low concentrations (i.e., ppb or less) of these volatile organic compounds can cause adverse health effects (Leidinger et al. 2014). The exposure to these landfill gases are largely through respiration (Palmiotto et al. 2014) and hence the releases of these volatile organic compounds into the atmosphere should be well managed.

Even so called environmentally friendly technologies such as pyrolysis and gasification used to produce value added products (e.g. oil, char and syngas) from municipal solid wastes produce gaseous pollutants including polycyclic aromatic hydrocarbons and fine particulate matter (Hajizadeh et al. 2011; Rochman et al. 2013). Polycyclic aromatic hydrocarbons impact both the environment (Sun et al. 1998) and human health largely acting as teratogenic, carcinogenic or mutagenic compounds (Ionescu et al. 2012; Moeckel et al. 2013). Also fine particulate matter have possibilities to associated with polycyclic aromatic compounds (Richter and Howard 2000) and those with diameter of ≤2.5 μm cause lung cancers due to deep penetration into lung tissues (Buonanno et al. 2011; Ionescu et al. 2013).

7.1.2.2 Contaminants to Water and Soil

Landfill leachate has been recognized as one of the main causes of groundwater contamination (Fatta et al. 1999). Leachate originates with infiltration of rain water or with an underflow of groundwater through waste deposits. The decomposing solid waste results in a liquid rich in inorganic and organic substances and this liquid is referred to as landfill leachate. Normally, leachate collects at the bottom most part of the landfill and can percolate into groundwater (Mor et al. 2006). Rainfall is mainly responsible for leachate generation (Tränkler et al. 2005) and moisture content of the solid waste also have a significant influence on the volume of leachate produced (Wijesekara et al. 2014).

Landfill leachate mostly contain four main classes of compounds namely inorganic macro- components, trace metals, dissolved organic matter and xenobiotics (Christensen et al. 2001). These compounds are mainly responsible for the pollution of soil and groundwater impacting both the natural environment and neighboring communities. There are health risks that could arise with consumption of contaminated ground water or fruits and vegetables cultivated using contaminated soil and ground water (Palmiotto et al. 2014). In addition to humans, landfill leachate has been identified as extremely toxic to many other organisms such as algae, higher plants, invertebrates and fish (Langler 2004; Di Natale et al. 2008). Several studies reported that trace metals such as Cd, Ni, Hg, Cu, Mn, Pb and Zn are present in leachates at elevated concentrations and the ability of these to bind with dissolved organic carbon for instance, humic, fulvic and hydrophilic acid enhances their dispersion across ecosystems (Asadi 2008; Wijesekara et al. 2014). Furthermore, dissolved organic carbon particles are responsible for the characteristic dark brown color of the leachates. The xenobiotic compounds (e.g. chlorinated aliphatics, aromatics hydrocarbons, halogenated hydrocarbons and phenols) and inorganic ions (e.g. nitrate, nitrite, ammonium, sulphate and phosphate) on the other hand also can severely impact living organisms (Asadi 2008; Mor et al. 2006).

In the latter part of this chapter we discuss how production of biochar from municipal solid waste could reduce landfill. Additionally, we discuss how this biochar also could be used to sustainably treat landfill leachate produced at legacy sites.

Development of environmentally sustainable strategies to mitigate pollutants of municipal solid waste is one of the biggest challenges that humans have ever faced (Wijesekara et al. 2014). Ideally municipal solid waste management systems should be designed such to treat waste based on quality, quantity and composition (Kalantarifard and Yang 2011). However, development of such sustainable management systems are a challenge largely because of complexity, variability, quantitative assessment of waste, inadequate technological resources, limited information about pollutants and a lack of positive attitude towards waste management (Ionescu et al. 2013).

Today there are calls for development of technologies to convert municipal solids directly into value added products. This creates an avenue to re-utilize municipal solids specifically to facilitate various environmental solutions. Pyrolysis of municipal solid waste is one such technology that directly adds value with conversion of municipal solids into biogas and biochar as final end products.

The biochar, produced has proven to possess excellent adsorption capabilities to remove impurities from both water and soil (Glaser et al. 2000, 2002). Compared to technologies such as incineration, pyrolysis uses less energy and also helps sequest carbon reducing greenhouse gas emissions into the atmosphere. Therefore, pyrolysis has potential to facilitate management of municipal solid waste and the end products of pyrolysis could also become a revenue stream for municipalities.

7.2 Municipal Solid Waste- Biochar Production

7.2.1 Production Technologies

Biochar is generally produced by thermochemical decomposition of biomass (organic matter of living organisms (plants and animal) and their residues) at temperatures of 200–900 °C (Lehmann and Joseph 2009). Traditionally, biochar was produced in earthen charcoal kilns where pyrolysis, gasification, and combustion processes were carried out in parallel (Brown 2009; Duku et al. 2011). Traditional charcoal-making technologies emit considerable amount of smoke, soot and combustible gases to the environment and are energy inefficient (Brown 2009). Hence, there has been a development of cost effective and environmentally friendly thermochemical conversion processes. Pyrolysis, carbonization and gasification

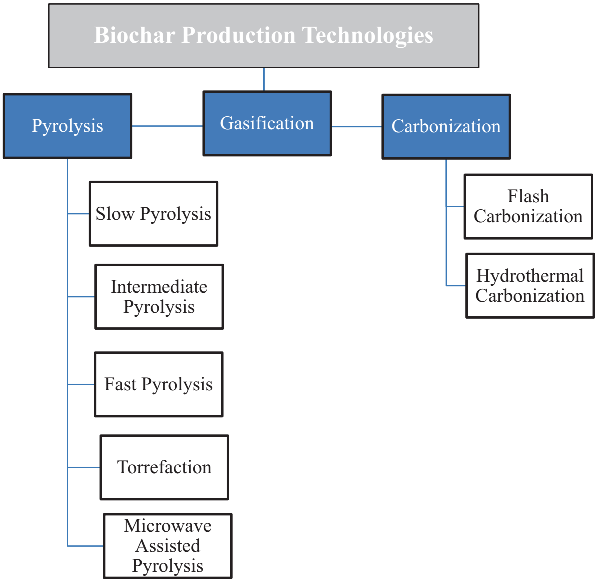

Fig. 7.1 Different technologies of biochar production: the "greener transformation" of municipal waste to a value- added products

processes are the main thermochemical processes that are used today to convert biomass to biofuels, gaseous products and other c-rich solid products (biochar) (Duku et al. 2011) (Fig. 7.1).

During pyrolysis, biomass is heated to a target temperature in the presence of little or no oxygen (Demirbas and Arin 2002). Due to the reductive atmosphere that prevails during formation of biochar, there is evaporation of Cd and Zn. However, Cu, Ni, and Cr are reduced to their elemental forms or sulfides (Dong et al. 2015). There are several pyrolysis technologies (e.g. fast pyrolysis, intermediate pyrolysis, slow pyrolysis, toreffaction, and microwave assisted pyrolysis) that can be used for thermochemical conversion of municipal solid waste into biochar (Mohan et al. 2014) and further details can be found in the later part of this chapter (Fig. 7.1).

Slow pyrolysis is carried out at a low rate of heating (lower than 10 °C/min) and a short residence time of few minutes to several hours is commonly applied to facilitate production of biochar. Fast pyrolysis is carried out at a higher rate of heating (~1000 °C/S) to produce bio-oils (as the major product (70%)) and biochar (Mohan et al. 2014). The yield of slow pyrolysis biochar is relatively high (35%) compared to fast pyrolysis (10%) and gasification (10%) (Sohi et al. 2009; Mohan et al. 2014). Torrefaction is a pyrolysis process, which is carried out at a low temperature (200–280 °C) to facilitate partial decomposition of biomass. There are numerous studies which has examined slow/moderate pyrolysis of municipal solid waste (Buah et al. 2007; Miskolczi et al. 2013; Kabir et al. 2015; Jayawardhana et al. 2017). But reports on the production of biochar via fast pyrolysis is limited (Wang et al. 2015).

Biochar yields from different studies have been summarized by Jayawardhana et al. (2018), and according to the study there is a huge variation in the observed yields (range between 14–66%). It has been further observed that the municipal solid waste biochar yields increase when rate of temperature increase is less and vice versa (Phan et al. 2008; Kabir et al. 2015; Zornoza et al. 2016; Jayawardhana et al. 2018).

Microwave assisted pyrolysis is a novel pyrolysis technique and may serve as an economically, and environmentally friendly biochar production process when comparing performance with conventional pyrolysis processes (Luque et al. 2012; Yu et al. 2017).

Hydrothermal carbonization is one of the most recently introduced carbonization processes and it reduces higher energy cost requirements of biochar production (Luque et al. 2012; Yu et al. 2017). The technology does not require a dry feedstocks and therefore has a reduced energy requirement (Lu et al. 2012b). The input energy requirements of hydrothermal carbonization is low due to the technology's ability to accommodate a feedstock with a high moisture content. During the carbonization process, the feedstock undergoes a series of simultaneous reactions, including hydrolysis, dehydration, decarboxylation, aromatization, and re-condensation (Libra et al. 2011). Flash carbonization converts biomass into gas at an elevated pressure (at about 1–2 MPa), a 30 min residence time and at a temperature range of 300–600 °C (Meyer et al. 2011).

Gasification converts biomass into a gaseous fuel as the primary product and liquid/solid as secondary products. This process requires a gasifying medium such as a steam of air, or oxygen to rearrange the molecular structures in solid or liquid biomass. Biomass is subjected to high temperatures in an aqueous media allowing transformation of carbon to a gaseous fuel (coal) (Lv et al. 2004). Pyrolysis process of municipal solid waste emits less toxic substances compared to combustion and gasification processes (Agarwal et al. 2015). To date majority of these municipal solid waste biochar production processes have been carried out in small scale or in laboratory scale. Designing a large scale municipal solid waste biochar production processes targeting a specific end product is challenging due to the complex and heterogeneous nature of municipal solid waste feed stocks.

7.2.2 Municipal Solid Waste Biochar Characteristics

The physicochemical characteristics (e.g. surface area, functional groups, particle/pore sizes, pH, ash content, moisture content, yield etc.) of biochar depends on the type, nature and origin of the feedstock and production conditions (Duku et al. 2011) (Table 7.1). It has already been shown that increasing pressure and decreasing peak temperatures increase biochar yields. Biochar produced at high temperatures has high aromatic content and high porosity (Table 7.1).

Table 7.1 Production processes of biochar at different temperatures with elemental contents

Origin of municipal solid waste	Thermochemical process	Pyrolysis temperature	Mobile matter	Fixed matter	Ash	C	H	O	N	Surface area	Pore volume	References
		°C	%	%	%	%	%	%	%	m^2/g	cm^3/g	
Sri Lanka	Slow pyrolysis	450	31.6	46.5	15.6	60.8	2.79	14.6	1.33	212.95	0.013	Jayawardhana et al. (2017)
Australia	Slow pyrolysis	450	11.9	13.0	72.7	68.6	4.33	20.1	6.09	–	–	Taherymoosavi et al. (2017)
		550	8.5	12.6	76.2	76.7	2.84	13.6	5.79	–	–	
		650	6.3	14.3	76.8	80.7	2.64	10.0	6.00	–	–	
USA (paper, textile, organic waste, plastic)	Slow pyrolysis	400	–	65.2	6.1	48.6	12.2	31.7	1.3	20.7	–	Jin et al. (2014))
		500	–	63.8	9.2	59.5	9.1	20.8	1.4	29.1	–	
		600	–	78.2	6.2	70.1	8.4	13.7	1.3	29.8	–	
China	Gasification	700	–	–	31.1	31.2	1.07	36.5	–	–	–	He et al. (2009)
		750	–	–	42.0	23.3	0.90	33.8	–	–	–	
		800	–	–	57.6	25.0	0.88	16.4	–	–	–	
		850	–	–	58.6	14.7	0.72	26.0	–	–	–	
		900	–	–	72.8	9.0	0.70	17.4	–	–	–	
		950	–	–	84.0	4.0	0.40	11.5	–	–	–	
	Slow pyrolysis	600	–	–	–	64.4	0.22	12.4	2.4	0.98	0.0003	Liu et al. (2017)
		700	–	–	–	64.1	0.21	12.8	2.8	28.4	0.01	
		800	–	–	–	64.8	0.23	12.6	2.7	112	0.04	
Korea	Hydrothermal carbonization	280	74.2	13.3	12.5	41.7	5.3	40.1	0.4			Kim et al. (2017)
Australia	Slow pyrolysis	450	11.9	13.0	72.7	68.6	4.33	20.1	6.1	–	–	Taherymoosavi et al. (2017)
		550	8.5	12.6	76.2	76.7	2.84	13.6	5.8	–	–	
		650	6.3	14.3	76.8	80.7	2.64	10.0	6.0	–	–	

7.3 Municipal Solid Waste Biochar As a Green Adsorbent for Contaminant Mitigation

Municipal solid waste derived biochar has been well studied for its ability to remove heavy metals, metalloids and organics (Agrafioti et al. 2014; Jin et al. 2014). Biochar has been examined to treat landfill leachate, as permeable reactive membranes and as landfill capping and results have shown promising outcomes. Several other studies have also shown its efficacy to retain nutrients in soil for plant uptake enabling the plants to tap into bioavailable nutrients over a longer periods of time (Milla et al. 2013; Liu et al. 2017).

The biochar from municipal solid waste is capable of removing two kinds of contaminants: organic and inorganic. The primary pathways for inorganic contaminant adsorption from aqueous media is via electrostatic interactions, ion exchange, chemical precipitation and complexation with functional groups. The most dominant route of entrapment is via surface reduction and adsorption on to surfaces of the biochar (Park et al. 2006). The schematic diagram of Fig. 7.2 illustrates the overall pollutant removal mechanisms of biochar.

The modes of removal of organic and inorganic contaminants using biochar from an aqueous medium tends to follow a certain pathway depending on the nature of the contaminant and its tendency to attach on to the surface of the carbonized and non-carbonized parts of the municipal waste biochar.

According to Chen et al. (2008), the adsorption of organic contaminant takes two pathways: i.e. by adsorption and partition onto carbonized and in non-carbonized fractions. Biochar derived from municipal solid wastes possess the same contaminant removal mechanisms that are detailed in Table 7.2.

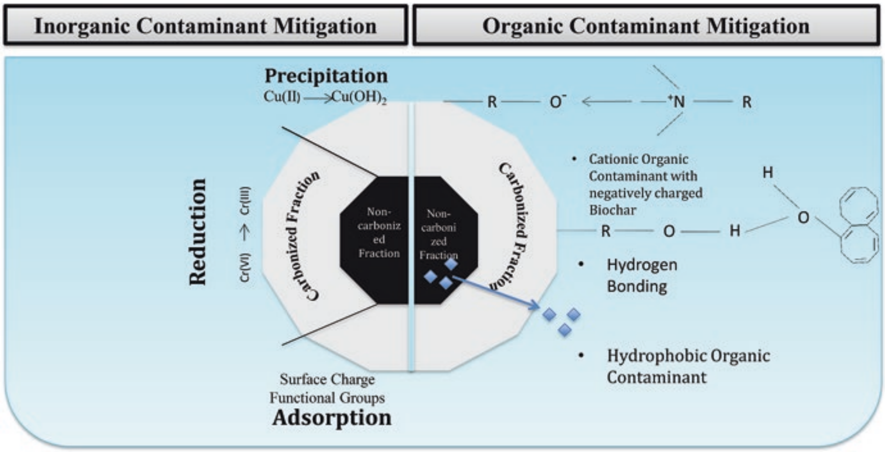

Fig. 7.2 Schematic representation of pollutant removal pathways observed in biochar produced using municipal solid waste

Table 7.2 Biochar pathways for contaminant removal

Biochar derived from different wastes	Trace metal(loid)	Mechanisms	Reference
Hardwood and corn straw	Cu, Zn	Adsorption	Chen et al. (2011)
Orchard punning biomass	Pb, Cr	Surface electrostatic interactions and surface complexation	Caporale et al. (2014)
Dairy manure	Cd, Cu, Zn	Precipitation and surface complexation	Xu et al. (2013)
Anaerobically digested garden waste	Cu, Zn	Chemisorption	Zhang and Luo (2014)
Sewage sludge	Pb	Adsorption due to cation release, functional groups complexation, and surface precipitation	Lu et al. (2012a)

7.3.1 *Leachate Treatment*

Removal of trace metals, for instance, Cd, Hg, Ni, Mn, Cu, Zn and Pb from leachates is important (Wijesekara et al. 2014). Most leachates have a blackish colored appearance and this is a result of dissolved organic carbon and trace metals. The degradation and release of dissolved organic and inorganic metals can cause leachate plumes in aquifers contaminating ground water (Christensen et al. 2001; Robinson 2005).

The heavy metals in landfill leachate are a hazard and new landfill management technologies aim to recovery these heavy metals as a secondary resource (Asadi 2008). The heavy metals are removed largely via sorption or precipitation from the landfill leachate. Biochar shows capacity to remove trace metals from both soil and aqueous media (Table 7.2). Due to high adsorption capacity of biochar derived from municipal solid wastes, it also has potential to remove trace metals from landfill leachate (Robinson 2005; Asadi 2008). Its ability to adsorb heavy metals arises from the electrostatic interactions between the carbonaceous surface and the positive metal ions. Biochar from municipal solid waste unlike other carbon based adsorbents contains metal oxide groups on the surface and few acidic oxygen groups as well that could make the adsorption more prominent with active sites of metal cations (Agrafioti et al. 2014).

In most developing countries, the municipal solid waste landfills are open dumps which makes leachate and gas management quite difficult at these sites (Vithanage et al. 2014). The gas emissions from municipal solid wastes are toxic and contains a wide range of volatile trace pollutants known as volatile organic compounds. The volatile organic compounds (VOCs) are the main reason for pungent odor that emits from these sites. These VOCs are highly carcinogenic as well as mutagenic when photo-oxidized (Srivastava and Mazumdar 2011; Jayawardhana et al. 2017). Benzene, toluene, xylene and ethyl benzene are the major constituents found in these volatile gases emited from these sites (Harkov et al. 1985; Robinson 2005).

The potential to use biochar derived from municipal solid waste to remediate these VOCs has been studied and proven promising (Jayawardhana et al. 2017). In this study, the municipal solid waste was made to pyrolyze at 450 °C and the biochar produced was analyzed for its behaviors with the gases pollutants. The adsorbents showed a low polarity index and high H/C ratios facilitating intermolecular interactions between the contaminant and the adsorbent surface. Hence, non- polar benzene was observed attaching onto the surface of municipal solid waste biochar effortlessly and as a consequence, a consistent removal of gaseous VOCs was feasible (Daifullah and Girgis 2003; Costa et al. 2012). A further analysis of the biochar revealed an insignificant amount of trace metals adsorbed onto the surface. Thus, the adsorbent showed promise towards removal of the hazardous gases from landfill sites (Jayawardhana et al. 2017).

7.3.2 Material for Permeable Reactive Barriers

Lot of studies have examined the suitability of different materials to use as permeable reactive membranes in landfills. Some of the materials examined include activated carbon, non- zero valent iron, etc. (Tratnyek et al. 2003; Turner et al. 2005). Understanding the characteristics of the above materials help to assess effectiveness of biochar produced from municipal solid waste as a PRB to remediate leachate from landfill. The main objective of these barriers are to intercept and remove contaminants as much as possible at the subsurface before the contaminants could reach groundwater (Thiruvenkatachari et al. 2008). The reactive barrier has to be a permanent permeable membrane placed across the path of a plume. At a natural gradient, the plume would pass though the reactive barrier and with entrapment of pollutants the contamination of ground water downstream can be minimized.

Materials that are used in these barriers, typically, have an adsorptive surface that demonstrate good hydrophobicity and they also are insoluble. As explained in the previous section biochar has these properties that enable entrapment of contaminants on its surface and this prevents any change of ground water quality parameters such as pH and dissolved oxygen (Panturu et al. 2009; Obiri-Nyarko et al. 2014).

Commercially, activated carbon has been the preferred choice for reactive barriers to adsorp contaminants from water. However, it has not been effective when scaled up to mitigate large plumes. At large scale, the associated cost of these reactive barriers are also significant (Ali and Gupta 2006). Biochar on the other hand is low cost and comparatively have shown to be more effective than activated carbon. Biochar produced sustainably using municipal solid waste on the other hand is not only cost effective it also helps better manage the disposal of organic solid waste. (Mor et al. 2016; Jayawardhana et al. 2017).

Agrafioti et al. (2014), studied removal of As (V), Cr (III) and Cr (VI) form wastewater using biochar derived from municipal solid waste. Similarly,

Table 7.3 Potential of municipal solid waste biochar for contaminant mitigation

Feedstock and contaminant type	Temperature attained at pyrolysis of MSW (°C)	Contaminants mitigated	Contaminant conc.	Adsorption capacity	Reference
MSW (inorganic contaminant mitigation)	400	As(V)	5–400 ppm	24.2 mg g^{-1}	Jin et al. (2014)
	500			24.49 mg g^{-1}	
	600			18.06 mg g^{-1}	
	500 (activated)			30.98 mg g^{-1}	
	300		0–100 ppb	–	Agrafioti et al. (2014)
	300	Cr(VI)	0–800 ppb	–	
	600	Hg	0.042 ppb	26.8 µg g^{-1}	Li et al. (2015)
	600 (chemically activated)			118.1 µg g^{-1}	
	600 (chemically and microwave activated)			157.7 µg g^{-1}	
MSW/urban food waste (organic contaminant mitigation)	250	Acridine Orange	10–100 ppm	60 mg g^{-1}	Parshetti et al. (2014)
				75 mg g^{-1}	
				79 mg g^{-1}	
		Rhodamine	10–100 ppm	51 mg g^{-1}	Parshetti et al. (2014)
				62 mg g^{-1}	
				71 mg g^{-1}	
	450	Benzene	30–300 ppb	576 µg g^{-1}	Jayawardhana et al. (2017)

Jayawardhana et al. (2017), examined removal of benzene using biochar derived from municipal solid waste. When effectiveness of biochar derived from husks was compared with biochar derived from municipal solid waste, the latter was found to be 1.3 times more effective at adsorbing pollutants. All of these studies were based on the adsorption mechanisms that were detailed in the previous sections.

From amongst the pathways mentioned in the previous sections, the plausible route of heavy metal adsorption onto municipal solid waste biochar is by electrostatic attractions. Due to the available pore volume and surface area, the metal cations are easily bound to the carbonaceous sites of the biochar (Li et al. 2015). As far as the inorganic contaminants are concerned, the forces involved are hydrogen bonding, along with electrostatic interactions and van der Waals forces and this has been explained examining adsorption of Acridine Orange and Rhodamine onto biochar produced from urban food waste (as in Table 7.3) (Parshetti et al. 2014).

7.3.3 Material for Landfill Capping

Some of the main challenges associated with sustainable management of landfills are the reduction of greenhouse gas emissions and mitigation of odor (Lamb et al. 2014). To reduce above impacts several technologies have been developed such as gas-collection systems, compacted clay covers and composite covers. However, due to lack of technical knowledge and economic complications, construction of effective gas-collection systems to manage methane emissions is still a difficult task for many landfills throughout the world (Yang et al. 2017). Also, the municipal solid wastes of many developing countries is mainly consisted of organic matter. Specifically there is a great amounts of food waste and the high moisture content that is associated with food waste creates a conducive environment for production of methane (Hui et al. 2006; Zhang et al. 2010). Under such conditions, collection of methane is a big challenge even for the landfills that are fitted with gas-extraction systems (Yang et al. 2017).

Landfill covers are one the most promising methods to control emission of gases from landfills (Yuen et al. 2013). Impermeable barriers made from compacted clay layers are most suitable for the construction of landfill caps (Yuen et al. 2013). However, shorter life spans, difficulties to prevent percolation of water through cracks and the reduced interaction of methane with oxygen preventing oxidation of methane are main disadvantages of clay clapping (Albrecht and Benson 2001; Vasudevan et al. 2003; Abichou et al. 2004). Hence, biologically active covers or filters are considered vital to mitigate landfill gases emissions (Bogner et al. 2008; Yang et al. 2017).

The mechanism behind the use of biologically active barriers is oxidation of methane to carbon dioxide by facilitating an environment for methanotraphic microorganisms (Karthikeyan et al. 2015). Many types of biologically active materials such as sewage sludge, compost and mechanical biological treatment residues have been examined in previous studies (Einola et al. 2008; Mei et al. 2016; Lee et al. 2017). Lately biochar has also been examined and found to be a promising material to mitigate methane emissions from landfills. Biochar is efficient as a biologically active material due to its distinctive physicochemical characteristics. The large specific surface area and the reduced particle size of biochar enhances contact between methane, oxygen and methanogenic microorganisms, increasing the rate of methane oxidation (Yang et al. 2017). The biochar derived from municipal solid waste is not only cost effective it also enables re- utilization of a secondary resource, in this instance to mitigate pollution.

Phytocapping is another technique utilized to mitigate landfill gas emissions. That practice employs the growth of dense vegetation on a layer of soil that acts as a top cover for landfills. Studies have shown that phytocapping can also be enhanced by mixing biochar with the soil layer (Lamb et al. 2014).

7.4 Municipal Solid Waste Biochar for Resource Recovery

7.4.1 *Waste to Energy*

Fossil fuel combustion and industrial processes are responsible for 65% of CO_2 and many other toxic gaseous (e.g. volatile organic compounds, carbon monoxide (CO), Nitrogen oxides (NO, NO_2), particulate matter etc.) emissions into atmosphere (Hossain et al. 2008). Due to increase of global warming, there is worldwide effort to control release of these greenhouse gases into the atmosphere. Accordingly, there are stringent regulations being enforced to mitigate greenhouse gas emissions from environments such as landfills. Therefore, there is much interest to generate energy from municipal solid waste to minimize its discharge into landfill.

There are four main pathways to convert municipal solid wastes into energy. They are thermal conversion, thermochemical conversion, biochemical conversion and physio-chemical conversion (Gumisiriza et al. 2017). Thermochemical conversion technologies directly produce heat and energy while thermochemical, biochemical and physiochemical technologies first produce secondary energy carriers which can be used for the production of energy as heat or as electricity (Gumisiriza et al. 2017) (Table 7.4).

Direct conversion of biomass to heat via burning is referred to as direct combustion (Clini et al. 2008). The most primitive way of using direct combustion is burning dry biomass for the generation of heat for cooking. Direct combustion of biomass in furnaces is also carried out by industries to generate thermal energy requirements for boilers (Gumisiriza et al. 2017). The steam generated by boilers can then be used to drive turbines to generate electricity (Chambers 2004).

Gasification is the partial combustion of solid waste materials at higher temperatures (700–1500 °C) and pressures exposed to a low oxygen environment for a few seconds to minutes (Mohan et al. 2014). The end product of gasification is syngas, a mixture of H_2, CO and CO_2. Temperature, heating rate, pressure, and the gas

Table 7.4 Conversion pathways of municipal solid wastes

Conversion pathway	Method	End product	Reference
Thermal conversion	Incineration	Heat and electricity	Gumisiriza et al. (2017)
	Direct combustion		
Thermochemical conversion	Gasification	Syngas	Matsakas et al. (2017)
	Pyrolysis	Biochar, bio oil	
	Torrefaction	Stabilized friable biomass	
Biochemical conversion	Anaerobic digestion	Biogas	Gumisiriza et al. (2017)
	Anaerobic fermentation	Ethanol	
Physio-chemical conversion	Transesterification	Biodiesel	

Table 7.5 Pyrolysis classification

Thermal conversion process	Temperature range (°C)	Heating rate (°C/min)	Residence time	Product
Slow pyrolysis	350–800	Slow, (<10 °C/min)	Minutes–hours	Biochar
Intermediate pyrolysis	350–800	Medium	Minutes–hours	Biochar
Fast pyrolysis	400–600	Very fast (1000 °C/s)	Few seconds	Bio oil

composition under which feedstocks are treated determine the composition of the resulting gas mixture (Mohan et al. 2014). Syngas can be used in fuel cells, as a synthetic fuel and as a chemical feedstocks (Verma et al. 2012). However, there is still only a handful of gasification plants worldwide (Arena 2012). Flue gas released by gasification plants consist of acidic gases (e.g., NO_x and hydrogen chloride), organic pollutants (dioxins) and particulate matter (Matsakas et al. 2017). Emission of these are controlled by use of electrostatic precipitation, bag filters and slaked lime (Arena 2012). One major draw backs of gasification is the additional cost associated with cleaning the syngas. There are also additional operational costs associated with cleaning the tar that gets formed which is responsible for corrosion, blocking and fouling of gasifies (Matsakas et al. 2017). Fluidized bed gasifiers, cyclone gasifiers, entrained flow gasifiers and packed-bed gasifiers are widely used in gasification (Klinghoffer and Castaldi 2013).

Pyrolysis is the thermochemical conversion of MSW biomass at 200–900 °C exposed to a no/limited oxygen environment (Lehmann and Joseph 2009). Depending on the rate of heating, pyrolysis is divided into three main categories; namely fast pyrolysis, intermediate pyrolysis and slow pyrolysis (Mohan et al. 2006) (Table 7.5).

Characteristics and yield of pyrolysis products vary with the properties of feedstock, pyrolysis temperature and heating rate (Ahmad et al. 2014). Reactors used in large scale MSW pyrolysis are rotary kilns and tubular reactors. Lab-scale studies, however, have been carried out in fixed-bed and fluid bed reactors. Efficiency of pyrolysis can be improved by sorting and drying of MSW prior to pyrolysis.

Torrefaction is a thermochemical process carried out at a 200–300 °C temperature range with a low rate of heating (Mohan et al. 2014). Residence time of torrefaction vary from few minutes to several hours (Matsakas et al. 2017). Based on applied temperature, torrefaction can be categorized as a light (below 240 °C) or a severe (above 270 °C) torrefaction process (Bilgic et al. 2016). The major product of the process is char and it is able to retain up to 96% of its chemical energy (Gumisiriza et al. 2017). Hence, char can be used as a substitute for coal/charcoal and utilized in power plants, entrained-flow gasifiers and in small scale combustion facilities as a high quality fuel (Uslu et al. 2008).

Biodiesel produced by transesterification of tryglyceride oil with monohydric alcohols is another alternative fuel. It is nontoxic and can be produced using different waste cooking oils such as palm, soybean, canola, rice bran, sunflower, coconut, corn oil, fish oil, chicken fat, etc. (Hossain et al. 2008).

7.4.2 *Nutrient Retention and Recovery*

Because of the high carbonaceous constituents and its unique properties, municipal solid waste derived biochar serves as a better soil amendment than commercial activated carbon.

Municipal solid waste derived biochar and its priming effects on soil have been investigated to understand its impact on seed germination. Different biochar have varying fertilizer properties and the influence on the growth rates of plants also differ. Biochar can induced either a positive or a negative priming effect on soil (Milla et al. 2013; Liu et al. 2017).

Biochar derived from municipal solid wastes also improves soil pH and cation exchange capacity and as a consequence there is direct implications on plant growth. The increase of carbon content that results in with application of biochar also increases the water holding capacity in soil. As a result, there is retention of water and this has impact on heavy metal retention and release reducing its bioavailability (Glaser et al. 2002; Ahmad et al. 2014). Research shows that there are significant improvements to plant growth and seed germination when soil is amended with biochar and its impact is further enhanced when mixed with organic or inorganic fertilizers (Lehmann et al. 2011; Zhou et al. 2017).

7.4.3 *Hybrid Composting and Land Application*

Table 7.6 shows the concentrations of available trace metals in biochar derived from municipal solid wastes (Chen et al. 2014; Jin et al. 2014). Insignificant trace metal content of MSW-BC facilitates the use of it as an adsorbent without having further constrain to the environment (Jayawardhana et al. 2018). At the same time, this encourages MSW-BC use in compost and agriculture. However, it is indeed important to assess the trace metal concentrations frequently since there might be chances to have high metal concentrations which is not suitable for composting and/or agriculture use (Chen et al. 2014). Furthermore, it has been reported that MSW-BC stimulates Soil Organic Carbon (SOC) mineralization but rates decreased with time

Table 7.6 Trace element analysis for biochar derived from MSW

Study	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
	mg/kg								
Jin et al. (2014)	12	5	64	101	–	–	143	10	213
Chen et al. (2014)	–	3.37	100.3	202.4	31,000	749	–	51.5	–
Jayawardhana et al. (2018)	–	–	9.27	10.9	1810	305	1.8	2.5	82.8
Taherymoosavi et al. (2017)	8	3	35	163	–	–	45	192	987
450 °C									
550 °C	9	<1	29	187	–	–	23	193	791
650 °C	7	2	29	160	–	–	18	160	735

in dry land. Since, priming direction varies from positive to negative in the longer term, biochar amendment may suppress SOC mineralization (Liu et al. 2017). Hence, MSW-BC has been proposed as an appropriate management tool for increasing soil organic C storage, which is beneficial for fertilizing soil and fighting climate change.

Biochar addition increase soil pH, cation exchange capacity, electric conductivity, nutrients and water retention. Municipal solid waste derived biochar is capable of bring about positive outcomes for acidic arid soils. The properties of municipal solid waste derived biochar vary with production temperature, technology and application rate (Ahmad et al. 2014). Agronomic research reveal that biochar application overall improves crop productivity and has shown to support crop growth even under stress conditions (Seneviratne et al. 2017). The biochars ability to promote soil microbial activities growth and water retention (Bandara et al. 2017) is encouraging and future research should further examine the potential of biochar derived from municipal solid waste. Biochar also has excellent solute adsorption capacities. However, only few studies have investigated its applicability as a nutrient carrier to extend its use as a slow-release fertilizers. Few studies have shown that biochar is a nutrient-impregnated material, which has slow releasing properties similar to a slow releasing chemical fertilizer (Gwenzi et al. 2017). Biochars' ability to slowly release nitrate suggests a potential mechanism to deliver nitrate to plants facilitating better retention of nitrate in agronomic systems (Hagemann et al. 2017). To date, there is however, little evidence on biochars' impact on compost and on crop growth and future studies should particularly examine the potential of MSW-BC to enhance properties of compost.

7.5 Remarks

Biochar production, from municipal solid waste, undoubtedly reduces biomass wastage particularly municipal solid wastes that are otherwise a challenge to dispose. It is one of the greener approaches to sustainably dispose and recover nutrients that are present in municipal solid waste. Biochar derived from municipal solid waste provides opportunities to better manage landfills for instance, by facilitating treatment of leachate, by enabling its use as a material suitable for capping, permeable reactive barrier and as a green adsorbent to reduce greenhouse gas emissions. In addition to its ability to reduce greenhouse gas emissions, biochar is able to adsorb volatile organic compounds, organic pollutants (pharmaceuticals, polycyclic aromatic hydrocarbons, pesticides etc.), trace metals and nutrients. A further improvement of biochars' adsorption capacity may enhance its contaminant remediation potential. This can be approached by modifying the properties of biochar, specifically varying the pyrolysis temperatures and by segregating different organic solids present in the municipal solid waste feedstock.

In addition to making use of municipal solid waste to remediate the environment, research should focus on also identifying other possible beneficial applications to maximize reuse of municipal solid wastes. This would necessitate development of technology to facilitate for example chemical modifications of the biochar or nanoparticle impregnation to further improve its adsorption capacity.

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