Biomass valorization and phytoremediation as integrated Technology for Municipal Solid Waste Management for developing economic context

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Abstract

Municipal solid waste (MSW) has ranked among the most detrimental global issues of the decade, where it has been induced by the population trends, urbanization, and economic growth. The majority of conventional pollution treatment methods involve high capital and maintenance costs with sophisticated instruments and technology. Biomass valorization and phytoremediation has been described to be an effective and practicable alternative for expensive, conventional engineering techniques in managing MSW and remediating contamination. Modern biomass valorization methods are promising technologies that provide effective MSW reduction, at the same time providing measures for removing pollutants from leachate with its particular focus on biochar, which is resulted by torrefaction of the perishable waste. The simultaneous ability of phytoremediation to remove many types of contaminants in leachate by significant amounts is emphasized in the context with considerations to the challenges in the sector. Phytoremediation is limited by several factors such as contaminant specificity, time consumption, and some external factors, while biochar applications are limited due to substrate specificity. The study aimed to review scientific literature to provide a platform for biomass valorization and phytoremediation integration for developing economy context.

Keywords Waste to energy · Incineration · Pyrolysis · Biochar · Landfills · Composting

1 Introduction

Waste is considered as a by-product of most human activities where it has become inevitable with the modern consumerism based economic lifestyle. Municipal solid waste (MSW) is defined as domestic refuse from everyday items, including commercial and institutional wastes, street sweepings, and construction debris [1, 2]. According to the projections, by 2025, per capita MSW generation will reach approximately 1.42 kg with a cumulative global waste generation amount of 6.1 million metric tons for 4.3 billion urban residents [3]. Potential environmental and health consequences are reported to be varied with the diversified nature of the waste composition and generation rate as driven by economic development and rising living standards [4]. The waste composition of a particular community varies with the socio-economic status and lifestyle of the specific residents as they influenced by all of the above factors [5]. The waste composition may further be influenced by the frequency of waste collection, together with its local waste management and disposal measures [6]. MSW composition in a waste stream can be broadly classified into biodegradable and non-biodegradable waste, where biodegradable fraction can be broken down into simple elements through microbial activity [7].

In the global context, a prevalent portion of waste comprises of food and green waste, making up 44% of global waste followed by 17% of paper waste and 12% of discarded plastics [8]. It is demonstrated that typical waste streams of

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low-income countries contain a significant percentage of organic matter, making up around 56% [8, 9]. Throughout the world, almost 36% of the generated waste is disposed in landfills, while 33% of waste ending up in open dumps remaining devastating environmental and health issues. Only about 19% of waste turn recovered through recycling and composting, while 11% undergo incineration treatments [3]. Apparently, by 2016, 28 European Union member countries have reported to send 38.8% of waste into landfills while 53.2% was recovered by treatment options [10]. Some EU member countries, including Italy and Belgium have observed to recycle more than 70% of their generated waste while some other countries (Romania, Bulgaria, Finland, Sweden and Greece) preferably move towards landfilling option [10]. However, in the majority of developing countries accentuated to South Asia, open dumping is the most widespread method in which uncontrolled disposal of waste is typically undertaken [7, 11].

MSW can lead to critical environmental and health issues when they are improperly managed and handled. Landfills and open waste dumps remain not only the most common measure of waste disposal due to its viability in terms of economy however, also one of the most prominent pollution sources mainly due to leachate generation [12, 13]. Leachate is a toxic liquid generated in landfills and open dumpsites as the rainwater and moisture present in waste infiltrate through various layers of MSW, carrying loads of pollutants with it. Leachate comprises a wide range of organic and inorganic material, contributing to its complex nature [13–15]. Improper landfill leachate disposal accounts for surface and groundwater contamination to a substantial extent, even at trace concentrations [16].

Since typical landfills and open waste dumps are major sources of all three phases of waste products, solid (wastes), liquid (leachate), and gaseous (landfill gas), adequate pollution control measures should be engaged with the waste management systems [17, 18]. In order to remediate the waste, various techniques have been developed depending on either mobilization or immobilization processes [19]. The conventional treatment methods may be restricted due to the high operational costs while they are disclosed to be insufficient to fulfill the level of discharge requirement. The conventional treatment methods involve high capital and maintenance costs with sophisticated instruments and technology for pollution remediation [20]. Further, the complexity of landfill leachate makes it challenging to treat by a single universal method. Thereby research attention has been focused on the various treatment methods, with sufficient contaminant removal ability, cost, time, and skill needed.

MSW valorization concept can be simply described as the intended use of waste by converting their polymeric substances either to energy or chemical forms, where it allows to harness the untapped valuable fraction of waste. Apart from its basic application for waste-to-energy conversion, the amendment of odor and pollution from MSW and a significant reduction of the waste volume is highlighted [21]. However, among various valorization techniques, the most commonly used method is composting, in which separate collection of organic waste allows producing excellent quality compost or digestate to be used as organic fertilizer, predominantly in Europe [22]. Nevertheless, in most of the developing countries, a considerable fraction of the feed becomes compost residue and dumps back to the open dumpsites [23]. The ability of biomass valorization for sustainable waste management can be effectively utilized through the intensified application of its valuable products such as biochar for leachate treatment due to its enormous absorption capacity [24].

Phyoremediation technology is the application of plants in extracting and translocating contaminants to above-ground biomass. The technology can be limited by several factors such as contaminant specificity, time consumption, etc. [25]. Nevertheless, phytoremediation integrated with other technologies has been described to be effective and practicable alternatives for expensive, conventional engineering techniques for remediating contamination [26]. The necessity of an integrated solution has been pointed out in the scenario, which can effectively reduce MSW accumulation and related pollutants.

Competent integration of the above techniques are possible through biochar embedded wetlands, phytocapping, and utilization of contaminants accumulated biomass in valorization [25, 27]. These processes cumulatively act on removing certain pollutants in MSW streams as they have borne in leachate and air. The current study reviews scientific literature regarding the possible pollution removal using biomass valorization processes and phytoremediation in its regards to predominant pollution sources. Therefore the study aimed to eliminate the identified gaps between cumulative literature on the above aspects of biomass valorization and phytoremediation as an integrated approach.

2 Biomass valorization

2.1 Techniques used for biomass valorization

Valorization technologies are divided into thermochemical and biochemical conversion. When the chemical transformation of organic MSW is done by treatment with heat, that conversion is called a thermochemical conversion. If microorganisms are used instead of heat, then that conversion is called a biochemical conversion. Figure 1 summarizes feasible techniques for biomass valorization based on process objectives.

These techniques can be again categorized into two groups based on the purpose: energy recovery (waste to energy) and material recovery, as shown in Fig. 2. Energy recovery involves the recovery of heat and power by either direct

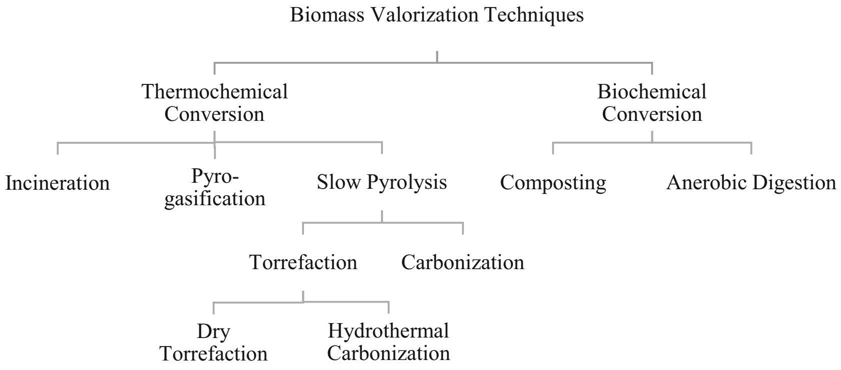

Fig. 1 Biomass valorization techniques

combustion or production of intermediate fuel (syngas, biogas etc.) [28]. However, these energy recovery techniques may not be feasible for every situation. Table 1 summarizes the common advantages and disadvantages of these techniques concerning implementation. Material recovery involves environmental remediation, utilizing bio-waste towards a value-added product [29], and recycling [30]. Thus, an integrated approach has to be implemented in order to manage MSW sustainably.

2.1.1 Incineration

Many countries have embraced incineration because of the reliability and waste volume reduction rate [31]. However, it is not economically viable for a small waste generation (<100 t/day) [32, 33]. Because of higher capital cost [34], problems associated with disposing of fly ash, and higher operational costs, authorities have to consider more cost-effective technologies to manage the disposal of MSW sustainably.

When combustibles are greater than 25%, ash content is less than 60%, and water content is less than 50%, bio-waste can be combusted without auxiliary fuel. Most MSW biomass fall above this combustion range, implying the requirement of either preprocessing (drying and sorting) or auxiliary fuel [35].

Although most frequently used combustors in practice, have a single chamber, multi-chamber combustors have been used to increase residence time and decrease soot and pollutant emission. According to Wickramasinghe et al. (2018), suspension combustor with two chambers can reduce unburnt hydrocarbons significantly (dry basis mass percentage of CH_4 up to 0.11 & that of CO up to 0.02) while maintaining freeboard temperature around 1050 °C [36].

Combustor (reactor) configurations can be categorized based on solid bed movement apart from the number of chambers: moving bed reactors and fixed bed reactors [37]. There are two types of fixed bed reactors: updraft and downdraft, based on the direction of gas flow. Here, the solid bed is not intentionally moved except the bed shrinkage due to gas generation. In an updraft fixed bed reactor, solid biomass enters from the top, and the oxidation agent enters from the bottom. Therefore, product gas flows upward [38, 39]. In a downdraft combustor, both fuel and air are fed from the top. Solid fuels are fed through a screw feeder while compressed air flowed down through the fuel bed. A grate supported at the end of the bed. Downdraft systems typically have a better carbon burnup ratio than updraft systems [40, 41]. According to Aerts and Regland (1990), gravel bed or exhaust gas temperature of downdraft combustor can be maintained around 1300 K while maintaining average particulate matter (PM) around 42 ppm (wt.) and NO in between 10 and 285 mg/L [41].

In a moving bed reactor, solid fuel particles are mixed intentionally. Fluidized bed combustors, which are consisted of fine solids, are the most common moving bed reactors.

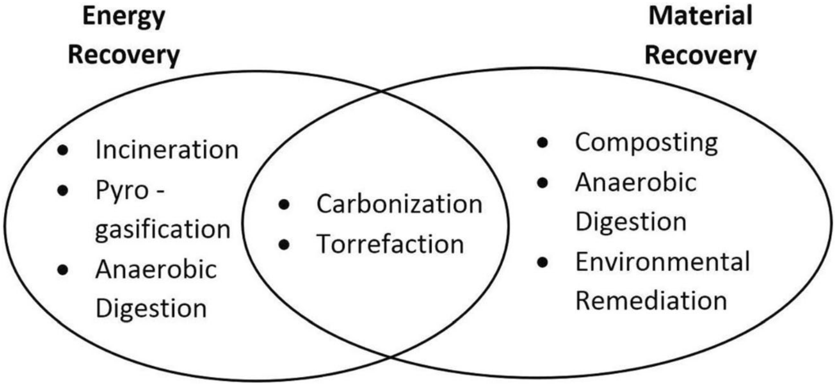

Fig. 2 Energy Recovery & Material Recovery

Table 1 Common disadvantages and advantages of WtE technologies with respect to the implementation

Technology	Disadvantages	Advantages
Incineration	High capital & operational cost Ash (bottom ashes & fly ashes)	High conversion rate Higher volume reduction
Pyro-gasification	Wet waste has to be pre-treated Pre-sizing	Different capacities Low resident time
Slow Pyrolysis	Low conversion rate Pre-sizing Requires inert environment	Different capacities Products can be used to MSW management
Anaerobic Digestion	Generally low conversion rate Microorganisms depend on the feedstock type	Different capacities Household unit Wet waste can be used

Here, the fuel bed is fluidized by the action of the air that flows from the bottom [42, 43]. Apart from that, rotary kilns and moving grate systems [44] are also used in different situations. Lombardi et al. (2013) have studied the combustion of healthcare waste in a rotary kiln, which was able to achieve a combustion temperature of 920–930 °C [45].

The major disadvantage of incineration as a WtE technology is ash. There are two ash types as bottom ashes (BA) and fly ashes (FA). The emission of FA can be minimized by practicing 3 T guidelines: high Temperature (> 850 °C), increased Turbulence (better mixing), and a longer residence Time (>2 s). However, entirely omitting of BA and FA is impossible; thus, either disposing of as landfill or reusing has to be followed after incineration [46].

2.1.2 Pyro-gasification

The thermal conversion of biomass includes the following steps: drying, pyrolysis, carbon gasification, and carbon oxidation. Thermal decomposition of biomass in an inert environment is referred to as biomass pyrolysis (devolatilization). However, gasification and oxidation of biochar (carbon) require gasification and oxidation agents, respectively. Because of the moisture and oxygen present in the municipal bio-waste, it is not possible to maintain an inert environment in the reactor, even though we supply an inert heat carrier. That is why this technique is referred to as 'pyro-gasification' [47].

The municipal bio-waste contains typically 20–70% of water [48]. Apart from that, cellulose, lignin, and hemicellulose are the main carbohydrate structures in bio-waste, and they usually cover 15–60, 1–25, and 5–40 weight percentages, respectively [49, 50]. In a pyro-gasification reactor, bio-waste is first dried and then pyrolyzed. Under realistic operational conditions, pyrolysis occurs at temperatures between 160 and 900 °C. The products of pyrolysis of cellulose, hemicellulose, and lignin under dry inert environment are listed in Table 2 [51–54]. For the representation simplicity, the hydrocarbon mixture is lumped and assumed as CH_4. Since the preferred product of pyro-gasification is syngas i.e. mixture of CO and H_2, Table 2 can be treated as an energy benchmark for different biodegradable MSW mixtures. Actual yields simply are not equal to Table 2 but depend on the heating rate, the operating temperature, the residence time, and the composition of the waste.

Since producer gas composition (syngas quality) depends on the homogeneous reactions, gas temperature and turbulence are crucial factors. Among homogenous gasification reactions, there are two most significant reactions (Eq. 1 & Eq. 2), which produce H_2 and CO, thus increases syngas quality. The first one (Eq. 1) is called steam reforming, which converts CH_4 into CO and H_2. The second one (Eq. 2) is a reversible reaction called water-gas shift reaction, which converts CO into CO_2 and H_2 [55].

Various technologies are employed for the gasification of bio-waste. All these technologies are the same as listed under incineration except for the gasification agent.

$$CH_4 + H_2O \rightarrow 3H_2 + CO \tag{1}$$

$$CO + H_2O \rightleftharpoons H_2 + CO_2 \tag{2}$$

2.1.3 Carbonization

Carbonization is a slow pyrolysis process, which converts organic material into highly carbonaceous material. The terms "carbonization" and "torrefaction" are often used interchangeably. However, their motivations are quite different, which

Table 2 Gas product yield (moles/kg-biomass on the as-received basis)

Components	CO_2	CH_4	CO	H_2
Hemicellulose	9.72	1.99	5.37	8.75
Cellulose	6.58	2.09	9.91	5.48
Lignin	7.81	4.43	8.46	20.84

results in different products, as shown in Table 3. A significant objective of carbonization is to increase the carbon fraction of solid content, as the name suggests, thereby not necessarily gives higher energy yield but higher energy density. As illustrated in Table 3, process conditions for carbonizations differ from that of torrefaction as it requires higher solid temperature and slower heating rate. As presented by Williams and Besler (1996), solid yield decreased as the operating temperature was increased but with the small effect of heating rate [58]. Table 4 summarizes relevant literature on carbon fraction and heating value of biochar produced by the carbonization of organic waste.

One advantage of all slow pyrolysis processes over incineration is the absence of solid waste. However, the presence of a hazarded substance in pellets arises health risks. Since not only low concentration but also attached to a solid body minimize the risk significantly. Thus, prevent further accumulation and poisoning.

2.1.4 Torrefaction

Torrefaction is also a slow pyrolysis process (Fig. 1) to maximize the energy density while achieving higher energy yield of the solid product ("char"/ "torrefied material"). There are two different production techniques: hydrothermal carbonization (HTC) and dry torrefaction (Fig. 1).

HTC process is carried out in subcritical water under mild temperatures (180–350 °C) [65, 66]. Therefor pressure should be enough to keep water as liquid. The significant steps involved during HTC are dehydration, polymerization, and aromatization. At the final stage, extra water with water-soluble ashes can be mechanically removed. Sometimes additional drying is required, such as heating [67]. HTC is able to achieve biochar mass yields of 19–67%.

In dry torrefaction, organic matter is heated in the absence of oxygen (or limited oxygen supply) with slow heating rates (0.2–12 °C/min), moderate residence times, and relatively low temperatures (<350 °C). Slow pyrolysis increases the carbon yield at least up to 40–65% depending on the temperature that is applied [68]. Either one of the following methods can supply the energy required to heat the solid phase.

(i) Directly from heat produced from exothermic reactions.

(ii) Direct/indirect heat transfer between heat carrier and solid.

The heat generated from the system will also be recovered to dry bio-waste for removal of excess moisture if needed (Table 5).

[56, 69].

Table 3 Comparison of Process Parameters and Product Yields (wt%) in carbonization and torrefaction

	Carbonization	Torrefaction
Temperature	>400 °C	<350 °C
Solid residence time	Hours ~ days	<3 h
Liquid products	30–53.6%	5–31.6%
Gaseous products	21.5–35%	11.2–15%
Solid products	16.2–35%	53.8–80%
References	[56, 57] and [58]	[59], [60] and [58]

Table 4 Carbon Content and Low Heating Values of Biochar

Fixed Carbon (wt%)	Heating Value (MJ/kg)	Reference
83.4	–	[61]
70.8–72.3	~26 (LHV)	[62]
70.3–95.3	–	[63]
80–82	29.9–30.6 (LHV)	[64]

2.1.5 Composting

Composting, which produces compost, is the stabilization of organic compounds by using mesophilic and thermophilic microorganisms. The final product is called compost. Most countries still use landfills instead of composting facilities to dispose of solid municipal biowaste. According to Matteson and Jenkins (2007), only about 15% of California's food waste is composted because of operational time and cost [70, 71]. However, composting is a must-have valorization technique in a circular economy. Even though the presence of pollutants in MSW based compost is an environmental risk, it can be overcome by preprocessing as well as post-processing while producing a fertilizer with not only macronutrients but also micronutrients [72, 73]. As an example, Shah et al. (2019) have shown that anaerobic degradation

Table 5 Comparison between HTC and dry torrefaction

		HTC	Dry Torrefaction
Process	Temperature (°C)	180–350	200–300
	Pressure (MPa)	1–25	(Atmospheric)
	Energy demand (kJ/kg)	900–1100	1300–1500
Product	Ash	Lower	Higher
	Fixed Carbon	Higher	Lower
	Moisture	Higher	Lower
	Energy density	Higher	Lower
	Heating value	Higher	Lower
	Hydrophobicity	Higher	Lower
	Grindability (HGI)	>44	Lower
	LHV (MJ/kg)	20–24	21–25

before conventional composting can be used to mitigate Pb and Cd associated health risks successfully [73].

For proper composting, the waste should have a carbon to nitrogen ratio (C:N) in between 20:1 and 40:1. The excess nitrogen may result in odor because of nitrous oxide and ammonia production, while insufficient nitrogen may prohibit microbial activities. Moisture content should be maintained between 40 and 65% (wet basis). At lower moisture levels (<40%), microorganisms' activities become slow, while at higher moisture levels (>65%), water limit air movement and lead to anaerobic conditions. At the end of the process, volume reduction is in the range of 40–80%, including moisture loss [74, 75].

The quality parameters of compost are not universal and hard to define with numerical bars [76]. However, according to Azim et al. (2018) and Rynk et al. (1992), mature compost applied as soil amendment should be dark brown or black, 7–8.5 in pH, around 10 in C: N ratio, higher than 1 in NO_3^-/NH_4^+ ratio and higher than 60 meq/100 g in Cation exchange capacity [77, 78].

2.1.6 Anaerobic digestion

Anaerobic digestion enables the exploitation of biogas produced from the mass fraction of solid waste [79, 80]. In addition to top product (biogas), a nutrient-rich bottom product can be used as either fertilizer or soil conditioner. Feedstock characteristics and process configurations are the main factors affecting performance. Cho et al. (1995) summarized the conversion efficiency in terms of methane yield of different feedstock and found higher efficiencies, such as 86% on a volatile solid basis [81]. The anaerobic digestion can be either wet or dry, and wet anaerobic digester needs a slurry with total solid (TS) around 12% [82]. Compared to wet anaerobic digestion, dry anaerobic digestion provides lower efficiency [83]. Due to stable digestion [84] and higher methane yield [85], two-stage fermentation has a more significant potential over one-stage fermentation. Several studies have evaluated the potential of landfill biogas generation [86, 87].

2.2 Uses of valorized products in MSW management

2.2.1 MSW biochar for contaminant removal in water

Among many products from various MSW valorization techniques, biochar has the best potential regarding MSW management [88]. Previous researches on MSW biochar show the opportunities to remove organic pollutants and trace metals from contaminated water and soil with the help of adsorption characteristics of biochar particles [24, 89, 90]. Jayawardhana et al. [91] highlight physical characteristics such as BET surface area (108.47 m^2/g), pore volume (0.013 ± 0.008 cm^3/g), and pore size (13.57 ± 0.06 nm), which justify the adsorption characteristics of MSW biochar. Table 6 summarizes the recent literature on contaminant removal using MSW biochar.

Since biochar show somewhat similar characteristics to activated carbon, researchers have used it to remove organic contaminants. Jayawardhana et al. [91] have shown the organic MSW based biochar can adsorb benzene from landfill leachate up to 576 μg/g at room temperature. Further studies on aromatic pollutants show higher Langmuir adsorption capacities for toluene (850 μg/g) and m-xylene (550 μg/g) [97]. Furthermore, Premarathna et al. (2019) and Ashiq et al. (2019) have reported tetracycline and ciprofloxacin removal, respectively, using biochar composites, which have been made by combining biochar from MSW as well as other sources with specially selected clay.

2.2.2 Air pollution control

Biochar can also reduce the overall landfill/ greenhouse gas emission [98, 99]. Eighty percent suppression of N_2O emission has been found in field applications and the grassland system [100, 101] Nevertheless, CO_2 emission has been reduced between 14 and 60% in field applications and maize growing [102, 103]. This reduction is mainly due to the respiration controlling by microbes, which have been grown due to the presence of biochar [89]. The presence of biochar reduces gas permeability up to 65%, compared with that of the bare soil [104], which leads to higher residence time for not only microbe respiration but also adsorption.

Further, the biochar amendment in soil cover of landfills can facilitate methane-oxidizing bacteria (*Crenothrix* and *Methylomonas* species), which remove methane near-completely for lower CH_4 influx rates (up to 518 g CH_4 $m^{-2}d^{-1}$) [27]. However, actual methane fluxes from landfills can vary widely depending on landfill age, landfill type, the number of hotspots, and etc., ranging from 0.0004 to 4000 g CH_4 $m^{-2}d^{-1}$ [105]. Therefore, an integrated mechanism of conventional gas recovery systems and biochar amended soil cover will be required to maintain a sustainable landfill

Table 6 Removal of contaminants using MSW Biochar

Pollutant	Adsorption Capacity (mg/g)	Reference
Ciprofloxacin	22	[92]
	67.36	[93]
m-xylene	0.55	[91]
Toluene	1.09	
Arsenic (V)	24.49	[94]
Tetracycline	78	[95]
Benzene	39.6	[91]
Copper	4–5	[96]

facility. A soil cover was proposed with amended steel slag in conjunction with biochar in order to mitigate the greenhouse emissions from landfills [106]. Despite emission reduction, an increase in GHGs emissions was reported by biochar due to the pyrolysis process conditions and composition of feedstock [107]. However, this risk can be overcome by maintaining the right process conditions and preprocessing the feedstocks. Hence, biochar produced by MSW may also be used in mixture with other biochars for landfill cover material, which will support the reduction of GHG emissions.

2.3 Other applications of valorized organic MSW

Apart from MSW management, valorized organic MSW can be used for various applications. Incineration can be used to generate heat and electricity. Even though it is quite feasible with respect to heat generation, the efficiency of electricity generation is somewhat low as 18% [108, 109].

Biochar can be used for compost value addition by producing hybrid fertilizers. Hybrid fertilizers were shown to improve the soil by becoming nutrient-enriched (anions nitrate and phosphate), slow-releasing of these nutrients and contaminants reduction [110–113]. As reported by Kizito et al. [114], enriched biochar significantly improves soil macronutrients (by 230%). Direct applying of biochar onto the soil, increases water-holding capacity [115], decreases nutrient leaching [116] and neutralize soil acidity [117]. According to Chan et al. [118], increasing of water-holding capacity caused by biochar leads to improved behavior of hard-setting soil. Ye et al. [119] show the possibilities of vegetation replanting of polycyclic aromatic hydrocarbons (PAHs) contaminated land by applying biochar and compost. According to Zhang et al. [120], biochar can be used to optimize composting itself by increasing oxygen uptake rates.

Pyro-gasification product, syngas, is mainly used as a fuel for conventional burner or boiler. Therefore, heating value has a massive impact when selecting the feedstock, the gasifier configuration, and the gasification agents. Usually, the syngas heating value ranges between 4 and 40 MJ/kg (Table 7). Some end applications require a higher heating value than others do [125, 126]. Liquid fuel also can be produced from syngas through the Fischer - Tropsch synthesis process.

Table 7 Syngas heating value w.r.t. feedstock

Feedstock	HHV (MJ/m^3)	Reference
Coconut shell, Mango pit, Ginisiriya	4.15	[121]
Urban solid residuals	5.4	[122]
Nutshell	14.55	[122]
MSW	7.5–18.6	[123]
Wood residuals	8	[124]

Methane from anaerobic digestion can be used to create electricity. Even traditional internal combustion engines can achieve 30–35% electrical efficiencies [127]. It can be used for cooking and heating as well. Besides, methane can be enriched, compressed, and then used as fuels for vehicles. Since it does not require extensive modification of either engine or vehicle, methane is a promising alternative fuel.

3 Phytoremediation of landfill leachate

Phytoremediation is a promising, plant-based technology in which the plants and their associated microbes are utilized to absorb and clean up environmental contamination through engineered constructed wetland systems. The ultimate aim is to either remove the pollutant from the contaminated media or to alter the chemical and physical nature of the contaminant so that it eliminates the risk to human health and the environment [128]. Various physical, chemical, and biological interactions take place in between plant and environment, which govern the phytoremediation process; nevertheless, they are present in the soil, water, or air [129, 130]. Phytoremediation has been demonstrated to be functioning in a range of metal, organic and inorganic pollutants and optimally in low to medium polluted media. The metals (Pb, Zn, Cd, Cu, Ni, Hg) and metalloids (As, Sb) are in a more significant concern for phytoremediation of leachate together with inorganic compounds such as Nitrate, Ammonium, and phosphate. The other organic pollutants which are remediated by Phyto techniques may range mainly from petroleum hydrocarbons (BTEX), polycyclic aromatic hydrocarbons, and explosives to chlorinated solvents [130, 131].

Different plant species are in interest according to the mechanisms intended to clean up certain chemicals depending on their characteristics and abilities [132]. Hyperaccumulator plant species have been discovered and demonstrated for their ability to grow in the high metal rich environment and accumulate higher amounts of metal contaminants in them. Mostly used plants include alfalfa (*Medicago sativa*), Cannas, Indian mustard (*Brassica junacea*), Canola (*Brassica napus*), and Kena (*Hibiscus cannabinus*) because of their fast growth, high biomass, and high tolerance of heavy metals. The selection of the most appropriate plant is one of the essential factors for the phytoremediation process [25].

Phytoremediation efficiency and mechanisms are determined by the type of contaminants, their bioavailability, and soil properties [128]. The root system of a plant provides a better surface area, primarily for the adsorption and accumulation of water and nutrients at the same time non-essentially for the contaminants in a medium [133]. Table 8 depicts different phytoremediation techniques which are capable of decontaminating various pollutants with the use of certain plant species. Thus, the applicability of the methods for

Table 8 Applications of different phytoremediation techniques for contaminants removal

Phytoremediation method	Process	Frequently used plants	Applicable contaminants	References
Phytofiltration	Application of plants for the removal of contaminants via the sequestration of them from contaminated waste water streams	Duckweed *(Spirodela polyrhiza L.)* Zealand watercress *(Lepidium sativum)* Water hyacinth (*Eichhornia crassipes*) Waterthymes *(Hydrilla verticillata)* Salvinia (*Salvinia minima)* Water hyacinth (*Eichhornia crassipes)* *Coontail (Ceratophyllum demersum)*	Zn, As, Cr^{6+}, Mn, Cd, Ni, Cu, U, Pb, Zn, Sr, As, B, Cd and Se	[134–137]
Rhizofiltration	Application of plant roots ability to absorb, accumulate and transform contaminants with the cooperation of rhizosphere microorganisms	Sunflowers (*Helianthus annuus* L.) Indian mustard (*Brassica juncea)* Bean (*Phaseolus coccineus*) Tobacco (*Nicotiana tabacum)* Rye (*Secale cereal)* Spinach (*Spinacia oleracea*) Cattail (*Typha angustifolia*) **Floating Aquatic plants-** Water hyacinth (*Eichhornia crassipes*) Pennyworth (*Hydrocotyle umbellata*) Duckweed (*Lemna minor*) Water velvet (*Azolla pinnata*) Pennycress (*Thlaspi arvense)*	Cr^{6+}, Mn, Cd, Ni, Cu, U, Pb, Zn, Sr, As, B, Cd, Se, Cs, Co, Hg and Mn	[134, 138–141]
Phytoextraction	Removal of accumulated pollutants with above ground plant parts after absorbing and translocation from the root zone	Indian mustard (*Brassica juncea*) Pennycress *(Thlaspi caerulescens)* Golden spring *(Alyssum wulfenianum)* Boxwood (*Buxaceae*) Canola (*Brassica napus*) Kenaf (*Hibiscus cannabinus L. cv. Indian*) Barley *(Hordeum vulgare)* Tall fescue (*Festuca arundinacea Schreb cv. Alta*) Alfalfa (*Medicago sativa*) Maize (*Zea mays*) Sudangrass (*Sorghum vulgare* L.)	Pb, Cr (VI), Cd, Cu, Ni, Zn, 90Sr, B, and Se	[142–144]
Phytostabilization	Stabilizing the contaminants in the soil by reducing their mobility and bioavailability preventing escaping and migration into groundwater. Thus, their ccumulation along the food chains is reduced	Tiny wild mustard *(Thlaspi goesingense)* Yarrow *(Achillea millefolium)* Guillaumin *(Alyxia rubricaulis)* Water velvet (*Azolla pinnata)* Globe yellowcress *(Rorippa globosa)* Blackberry nightshade *(Solanum nigrum)* Mountain gum **(***Eucalyptus urophylla)* Cowpea *(Vigna unguiculata)*	Ni, Hg, Mn, Cd, Pb, As	[145, 146]
Phytodegradation	Utilizes plants and micro-organisms in the process of uptaking, metabolizing and degrading the organic contaminants	White leadtree (*Leucaena leucocephala*) Madagascar periwinkle *(Catharanthus roseus*) Downy thorn-apple *(Datura innoxia)* Tomato *(Lycopersicon peruvianum)* Malcom's Blumea *(Blumea malcolmii)* Cockspur coral (*Erythrina crista-galli*)	Chlorinated solvents, Phenols, Herbicides, some air pollutants (NO$_2$ benzene, toluene, and formaldehyde)	[129, 147–149]

Table 8 (continued)

Phytoremediation method	Process	Frequently used plants	Applicable contaminants	References
		Green algae *(Chlorella pyrenoidosa*)		
Rhizodegradation	Organic contaminants in the soil can be broken down by microbial activities while the process can be enhanced and assisted by the plant root zone	Orange (*Citrus* sp.) Apple (*Pyrus* sp.) Mulberry (*Morus* sp.) Willow *(Salix nigra)* Orchardgrass (*Dactylis glomerata*) Smooth bromegrass (*Bromus inermis*) Tall fescue (*Festuca arundinacea*) Illinois bundle flower (*Desmanthus illinoensis* Rye-grass (*Lolium perenne*), Switchgrass (*Panicum virgatum*) Eastern gamagrass (*Tripsacum dactyloides*)	Petroleum hydrocarbons, Polycyclic aromatichydrocarbons (PAHs), Chlorinated solvents, Pesticides, Polychlorinated biphenyls (PCBs), Benzene, Toluene, Ethylbenzene, Xylenes	[150–153]
Phytovolatalization	The pollutants are taken up by plants and released into the atmosphere via transpiration after transforming them into volatile forms within the plants	Alfalfa (*Medicago sativa*), Indian musard (*Brassica junacea*) Canola (*Brassica napus*) Kenaf (*Hibiscus cannabinus*) Rabbit foot grass (*Polypogon monspeliensis*) Pickle weed (*Salicornia*) Parrot's feather (*Myriophyllum brasiliense*) Iris-leaved rush (*Juncus xiphioides*) Cattail (*Typha latifolia*) Club-rush (*Scirpus robustus*)	Chlorinated solvents (tetrachloroethane, trichloromethane, tetrachloromethane) Some inorganics (As, Hg, Se)	[154–156]
Hydraulic control	Controlling water table and soil field capacity with the use of highly transpiring plants affecting the existing water balance of a particular site	Poplar (*Populus trichocarpa*, *Populus deltoides*) Birch (*Betula* sp.) Willow *(Salix nigra)* *Eucalyptus* sp.	Water soluble organics and inorganics	[157, 158]

leachate and leachate contaminated soil treatment is apparent, where they contain substantial levels of organic and inorganic pollutants. However, the high concentrations of contaminants in landfill leachate become the main constraint for direct application of phytoremediation for treatment.

3.1 Landfill leachate

Landfill leachate consists with four main groups of chemical compounds including dissolved organic matters (COD, TOC and Volatile fatty acids), inorganic components ($Ca^{2+,}$ Mg^{2+}, $NH^{4+,}$ NO_3^{2-}, PO_4^{3-}, $Fe^{2+,}$ Mn^{2+}, Cl^-), heavy metals (As, Hg, Cd, Cr, Cu, Pb,) and xenobiotic organic compound (XOCs) [13, 159]. Basically, elevated levels of biological oxygen demand-BOD (4000–30,000 mg/L), chemical oxygen demand-COD (10,000–50,000 mg/L), total organic carbon-TOC (3000–20,000 mg/L) and ammonium nitrogen-NH_4^+-N (750–2000 mg/L) are observed in leachate of acetogenic phase, which presents a great potential of pollution [160–162].

Moreover, the presence of heavy metals and xenobiotic organic compounds such as phenols, halogenated hydrocarbons, and aromatic hydrocarbons enhance the pollution threat from landfill leachate. The high ammonia content and refractory organics reduce the biodegradability ($BOD_5/COD < 0.2$) of mature landfill leachate, which tends to make conventional treatment processes unsuitable for its treatment [163].

3.1.1 COD and BOD reduction

Plant roots had been demonstrated to be cooperated in the reduction of organic matter to a great extent due to the oxygen transfer by the root and rhizome tissues. The root system also provides a substrate for the attached microbes, carrying out the degradation process [164]. Thus, the plant root area of plants plays a significant role in the elimination of biodegradable organic matter content of the media. Nevertheless, some studies have reported that rather than biological processes, COD removal can be mainly driven by the physical processes in the system, including filtration by the substrate [165].

Stottmeister et al. 2003 explained that the oxygen input to the root zone by plants tends to direct degradation of pollutants and enhances microbial activities. Further, the study reported several plant species; turn, common reed, rushes, bulrushes, narrow-leaved cattail, broad-leaved cattail, yellow flag, sweet flag, reed grass, and sedges, that can be used for wetlands to treat leachate effectively. Plants that are grown in marshes may also be effective to withstand under any extreme rhizosphere conditions such as low milieu, high acidity or alkalinity, and toxic water components [166]. Madera and Valencia-Zuluaga, 2009 have examined phytoremediation ability for landfill leachate using factorial experiment design with two vegetal species and two support mediums. It has been observed the experimental design has removed 98% of color, 52% of COD, 84% of BOD together with 30% of NH_4-N in leachate from the selected landfill site in Columbia [167].

3.1.2 Inorganic components

Ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) removal A study has conducted by Erdogan et al. 2011, on leachate treatment using wild plants such as *Althea rosea, Cynodon dactylon, Inula viscosa, Melilotus officinalis* and *Thymbra spicata*. The test was conducted over two years of period and plants were observed with elevated N content, metals such as Fe and Zn and also the K and P amounts. The study concluded the ability of those plants to uptake considerable amounts of pollutants so that they are purposive in landfill restoration projects [148]. Madera-Parra et al., 2015 has demonstrated the removal of 72% and 67% respectively for both NH_4-N and total kjeldal nitrogen from landfill leachate using a mixture of *Colocasia esculenta, Gynerum sagittatum* and *Heliconia psittacorum* plants [168].

PO_4^{3-}-P removal Phosphate (PO_4^{3-}-P) removal occurs typically due to the activities of bacteria and plants in the remediation system. Plants can uptake PO_4-P while total phosphorus (TP) removal primarily relies on the retention capacity of the media and precipitation [169]. Phosphorus assimilation by plants during their growth is explained in numerous studies, emphasizing the role of plants in the P removal. Nevertheless, compared to nitrogenous compounds in the landfill, leachate mostly phosphate found in relatively low concentrations, i.e. 94–141 [170, 171], 2.2–10.3 [172, 173] and 5–260 mg/L [160]. Further, it has been noted that P can be converted and present in relatively less bioavailable forms which makes it a growth limiting factor for phytoremediation [174, 175]. However, including biochar may provide P into the plants, will reduce the effect of inadequate P for phytoremediation [176]. At the same time, toxic metals can easily be precipitated with phosphate, which immobilizes a fraction of toxic metal availability in landfill leachate [177, 178]. Moreover, the presence of the oxides of Fe, Al, and Ca in the leachate contribute to the removal of P due to the precipitation and adsorption [165]. Some experiments have concluded that the PO_4^{3-} removal by plants depends upon the seasonal variations and plant growth. Nevertheless, it has been observed that PO_4^{3-} removal is less dependent on temperature, while flow rates can significantly influence PO_4^{3-} removal efficiency [179].

3.1.3 Heavy metals

Several plants have been reported to be taking up heavy metals in order to decontaminate the leachate pollution. These metal accumulating plant species are capable of concentrating heavy metals such as Zn, Co, Cd, Pb, Ni, and Mn more than 100 to1000 times in comparison to the nonaccumulator (excluder) plants [180]. The up taking process is followed by the translocation of them into the above-ground parts and accumulation in plant tissues in less harmful forms [181]. This transfer of metals beyond the root cells, storing in tissues, and subsequent detoxification, together with sequestration, occurs at both cellular and whole-plant level [182]. The conversion of metals into less toxic forms can take place at any point in this translocation path [183].

Ultimate heavy metal removal may be commenced by the modification of physicochemical characteristics and (im)mobilization [184]. Nevertheless, a significant amount of removal can occur through the binding where heavy metal ions typically possess a positive charge, which enables rapid adsorbing and complexing into the substrate [185]. Sulfides, carbonates, bicarbonates and PO_4^{3-} in leachate can induce heavy metal removal due to the formation of insoluble salts via precipitation [177, 182]. Additionally, algae and microorganisms in the system are also capable of taking up heavy metals in leachate. Mycorrhizal fungi and root-colonizing bacteria can enhance the bioavailability of heavy metals in phytoremediation systems, which in conclusion, the rhizospheric microbial population can stimulate the plant uptake of heavy metal ions [185].

Removal of various heavy metals in landfill leachate has tested by various researches. Verma et al., 2015, has tested the ability of certain plant species to treat landfill leachate as an ecofriendly and economical treatment process. They have selected *Eichhornia Crassipes* (Water Hyacinth) in order to treat Nickel (Ni), Chromium (Cr), and Zinc (Zn) appeared in leachate. Heavy metals were reported to be reduced in 52, 96, and 92% for Chromium, Nickel, and Zinc, respectively [136]. Wei et al., 2006 demonstrated the ability of newly found Cd-hyperaccumulator, *Solanum nigrum* L. with considerable implications to their harvesting stages and frequency [145]. Jerez Ch and Romero, 2016 had evaluated the application of *Cajanus cajan* to remove chromium and lead from landfill leachates with observed ability to remove 49% of chromium and 36% of lead from dilute leachate [186].

3.1.4 Organic contaminants

The organic compound remediation relies heavily on their physicochemical characteristics and interactions with surrounding molecules. Thus, in phytoremediation of polluted leachate soil, pH, soil structure, texture as well as organic matter content are in consideration. Limited studies reported the application of phytoremediation for the removal of organic pollutants in landfill leachate. Research demonstrated the application of *Phragmites australis* plants for the removal of organic compounds, including phenol, bisphenol A, and 4-tert-butylphenol from synthetic landfill leachate. They have observed low-high removal efficiencies (9–100%) for studied compounds where phenol was removed entirely during the study conditions [187].

One study reports the ability of alfalfa plants to co-metabolize and degrades Tri-chloroethane (TCE) by methanotrophs where the plant transferred methane into the vadose zone from the saturated methanogenic zone [150]. Moreover, it was emphasized that due to the chemical and physical effects of plant exudates, soil pH might vary with the increasing microbial population, which can affect contaminant removal [150]. A study conducted by Omondi et al., 2015 investigated the application of water hyacinth (*Eichhornia crassipes*) for phytoremediation of landfill leachate containing PCB. Water hyacinth reduced the concentration of PCBs in the leachate over 15 days to 0.42 μg/L for the 15 μg/L initial concentration sample and to below 0.142 μg/L for the 10 and 5 μg/L initial concentration samples [188]. Table 9 depicts the various plant species used in phytoremediation of landfill leachate and their pollutant removal efficiency with regard to the potential pollutants.

4 Integration of MSW biochar and constructed wetlands

In recent years, significant research attention has been focused on the separate application of constructed wetlands driven phytoremediation and biochar for waste management approaches. Among several biomass valorization techniques, biochar has highlighted as an economical and effective valorization product with a recent research focus to be used for MSW management and leachate treatment in developing economic context [91, 161]. Biochar derived from biomass valorization process has a promising ability to directly utilized as a landfill capping and Phyto-capping material in order to eliminate gas and odor emissions from landfills [99]. However, improving the removal efficiencies by combined phytoremediation and valorization has been studied by a few researchers [198].

Biochar can be embedded into landfill covers and wetland substrates in order to enhance the removal efficiencies. These biologically active covers can act on mitigating greenhouse gases (methane (CH_4), Carbon dioxide etc.) and toxic volatile organic materials as escaped from landfills [199]. Since the biochar amendments have a high specific surface area, the contact surface for the methanogenic microorganisms remains high, which facilitates the efficient CH_4 oxidation [27, 200]. Research studies have demonstrated higher CH_4 removal rates ranging from 60 to 90% from biochar embedded landfill covers [200]. Phyto-capping also provides a vital solution for landfill gas emissions, where it involves a vegetation cover on the topsoil layer of landfill. Methane removal rates have been observed to be enhanced with the incorporation of biochar with the soil [201]. Apart from the mitigation of landfill

Table 9 Phytoremediation of landfill leachate

Plant species		Maximum removal efficiency %															Country	References
		COD	**BOD**	**TSS**	**TDS**	**Ammonium**	**Total N**	**Phosphate/ P**	**Cu**	**Fe**	**Pb**	**Ni**	**Zn**	**Cd**	**Mg**	**Cl**		
Water Hyacinth *(Eichorrnia crassipes)*		**54**	**59**	–	**57**	–	–	–	**87**	**88**	**84**	**82**	**90**	–	–	–	Pakistan	[182]
		68	**69**	**71**	**91**	–	–	**91**	–	**98**	**99**	–	**82**	**100**	**93**	**94**	Nigeria	[189]
Cyperus haspan		**39–92**	**60–78**	**60–100**	–	**60–100**	**34–67**	**30–54**	–	**35–59**	–	–	–	–	**29–75**	–	Malaysia	[164]
Duckweed *(Lemna minor)*		**39**	**47**	**33**	–	–	–	–	**91**	**77**	**78**	**76**	**83**	–	–	–	Pakistan	[180]
Imperata cylindrica		–	–	**98**	–	–	–	–	–	–	**56**		**6**	**16**	–	–	Malaysia	[184]
Typha latifolia		**81**	–	**35–88**	–	**60**	–	**45**	–	–	–	–	–	–	–	–	Turkey	[165]
Canna indica		**84**	–	**26–83**	–	**57**	–	**46**	–	–	–	–	–	–	–	–		
Cattail (Typha angustifolia L.)		–	–	–	–	**99**	–	–	**92**	–	**25**	–	**96**	**0**	–	–	USA	[190]
		59	**56**	–	**9**	–	–	–	**15**	–	**6**	**18**	**8**	–	**28**	**3**	India	[191]
		82	**91**	–	–	–	**96**	**94**	–	–	–	–	–	**100**	–	–	Thailand	[192]
	Young leachate	**97**	**99**	**88**	–	–	**43**	**99**	–	–	–	–	–	–	–	**25**	Thailand	[193]
	Stabilized leachate	**63**	**71**	**66**	–	–	**46**	**48**	–	–	–	–	–	–	–	**70**		
Pistia stratiotes		**52**	**54**	–	**56**	–	–	–	**72**	**83**	**77**	**69**	**80**	–	–	–	Pakistan	[182]
Willow *(Salix purpurea)*		**41**	**66**	–	–	**42**	**36**	–	**18**	**18**	–	–	**33**	–	**18**	**17**	Slovenia	[194]
Reed (*Phragmites australis)*		**96**	**92**	**28**	**28**	**100**	–	**100**	–	–	–	–	–	–	–	–	Bulgaria	[195]
		0–30				**51–80**		**18–20**		**11**						**3–13**	Italy	[196]
Phragmites australis and Typha latifolia		**50**	**59**	**33**	–	**51**	–	**53**	–	**84**	–	–	–	–	–	**35**	Slovenia	[197]

gases, this integrated technique will control landfill leachate while improving soil properties and plant growth in the phytoremediation system [24]. Figure 3 shows a proposed integrated landfill leachate treatment system based on MSW biochar in the Sri Lankan context. Authors have observed better results of the full system as a small scale set up for landfill leachate treatment [202]. Absorption of biochar can be further aggravated by allowing leachate to flow through a barricade system in which microbial treatment processes also can contribute to improving overall system performance [202].

Over the years, phytoremediation has been tested and applied through constructed wetland systems [164, 165, 168, 194]. It has been demonstrated as an appropriate and practical alternative, allowing landfill leachate to be discharged safely into the environment [163]. Constructed wetlands are the engineered systems that are designed to enhance the natural processes and interactions that are undertaken by plants [203]. This constructed wetland systems involve measures to allow leachate to be flowing through the shoot or root zone while they act on up-taking the pollutants from flowing leachate [204].

Floating constructed wetlands are adopted with plants, which are either having buoyant leaf bases or floating as a thin surface layer. The emergent plants create a floating mat on the substrate where the floating root system absorbs pollutants from the substrate [205]. The approach of using free-floating aquatic plants in the constructed wetland systems has been demonstrated in several research studies El-Gendy et al., 2006 has conducted experiments using a floating aquatic system of water hyacinth (*Eichhornia crassipes*) to investigate the ability to remove five heavy metals from leachate. The treatment system has shown better removals of copper, chromium, and cadmium up to 0.96, 0.83, and 0.50%, respectively, of their dry root mass [206]. Abbas et al., 2019 have tested the effectiveness of water hyacinth and water lettuce for the phytoremediation of landfill leachate through the floating bed technique. They have reported the removal of physicochemical parameters such as BOD, COD, TDS, pH, and heavy metals like Zn, Pb, Fe, Cu, and Ni from landfill leachate [182].

5 Challenges and future perspectives

5.1 Challenges

Apart from significant benefits, biomass valorization and phytoremediation based constructed wetlands pose some threats and challenges in implementation. Other than the inherent limitations of the valorization techniques (Table 1), the initial moisture content of MSW is one of the major challenges in terms of waste to energy conversion or biochar production, whereas excess heat may use in drying the feedstock. All thermochemical techniques generate waste gases with or without particulate matter, which raises challenges with respect to emission control. Further, the complexity of the MSW feedstock material has been a significant factor in the properties of biochar produced. The polluted substrate can also be regenerated by thermal treatment. At the same time, the composition of the feedstock materials may negatively influence the valorized products, especially for biochar production. Thus, it is a challenge to determine, define, and characterize biochar for different applications in waste management. Several biochar characterization techniques have to be applied for measuring surface area, pore-volume, capacity, and functional groups availability in different biochars in order to specifically determine their utilization. The characterization techniques may involve Fourier transform infrared spectroscopy (FTIR), Scanning electron microscopy (SEM), X-rays photoelectron, Raman spectroscopy etc. [207].

Secondly, all biochemical conversion techniques require longer residence time. Apart from that, an unpleasant odoron the premises is a difficult challenge to address. To overcome the odor, source management is essential in which food wastes and excessive moisture containing materials are separated before the composting processes, allowing their useful application in anaerobic digesters. Biochar may play a role in moisture and odor management in the composting process as well. Incorporation of exhaust air treatment systems such as biofilters and bio scrubbers can control the odor nuisance [208]. Continuous supervising and finding perfect operating conditions are of utmost

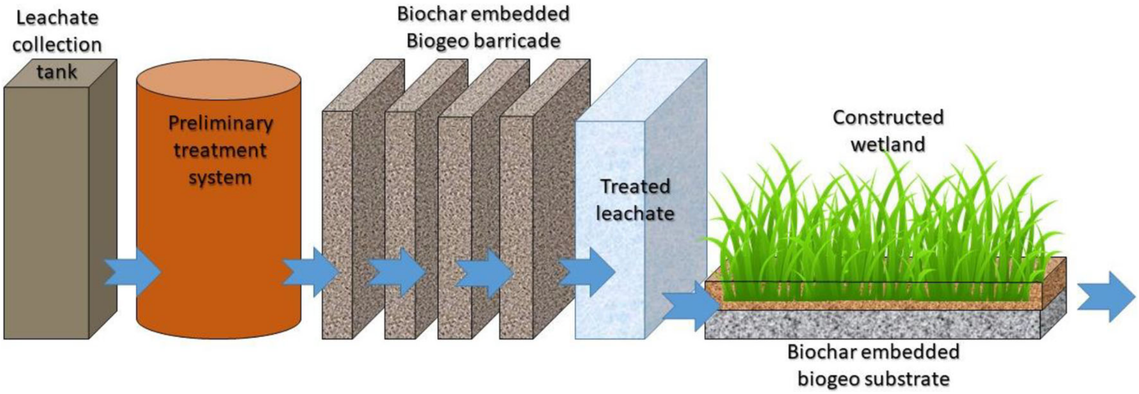

Fig. 3 A proposed integrated leachate treatment train with MSW biochar as a material

vitalimportance to overcome this challenge. Arising of environmental and health risks is associated with not only initial feedstock but also the process itself. Not like in thermochemical conversions, biochemical conversions produce solid waste (anaerobic digestion sludge/ compost residue), which generates further problems to relevant authorities.

More importantly, since leachate composition in a landfill may vary from time to time on a regular basis, a range of other factors such as precipitation, dilution effect, buffering capacity of the soil, should be concerned when applying the leachate treatment [209, 210].

- The treatment processes may limit by climatic conditions and soil factors in Phyto techniques as well as the characteristics of feedstock materials and temperatures used in the valorization
- Secure disposal of the polluted substrate is required after the treatment since they contain absorbed hazardous contaminants
- When plants are integrated (phytoremediation), the remediation process is more time consuming
- The plants should have the ability to grow up and persist in the contaminated media whereas dilution or pretreatment may be essential
- In case the contaminated plants may involve in natural food chains there is a possibility of bio-magnifying the contaminants
- Introduction of non-indigenous species for phytoremediation purpose may affect biodiversity
- Phyto techniques may be restricted mainly due to the low biomass and slow growth rate of plants
- In phytoremediation, roots should be in contact with the contaminants to be removed [211–213]

However, all of the technologies are important in managing MSW with unique advantages and disadvantages Selecting the best option based on the economic level and its scale for a particular waste management system is a challenge for a Local Authority. It may require improving the existing technologies, integrating them, and developing new ones like the aforementioned "biogeo barricade". Challenges concerning biogeo barricade are reusability and saturation time, which would depend on the concentrations in the leachate. The primary dispute is the capacity of the biochar as it is produced by the composted residue, which does not provide a high specific surface area. Phytoremediation may be another technique that can be integrated with the treatment train after constructed wetland will increase the treatment potential [175].

5.2 Future perspectives and recommendations

- Acquiring details on the composition and characteristics of feedstock is a prerequisite for valorization since they are determinant for the treatment efficiencies and properties of end products. Studies and on feedstock properties and their capacities on waste management approaches have to be conducted with the predictions of their suitability and availability
- The application of genetic engineering technologies is in concern to enhance the growth rates of plant species in combination with hyperaccumulating genes to be used in the waste management approaches
- Assessment of integrated systems with MSW conversion to biochar has not been examined for small and medium scale landfills
- High energy crops, producing high biomass, have not currently received sufficient research focus in the field of phytoremediation and landfill capping. Application of high energy plant species in Phyto-capping requires further studies and work to be conducted in order to achieve a sustainable treatment process. Subsequently, the plans can be effectively used for the energy and compost production via valorization techniques

Recommendations Biomass valorization and phytoremediation have been studied and reviewed as successful methods for MSW management specifically for open dumps and landfills, which produce enormous amounts of leachate. Some particular techniques are highlighted and recommended in the developing economic context such as biochar and constructed wetlands due to related low cost and high performances. Nevertheless, determining, defining, and characterizing valorized products for different applications in waste management is a challenge in which further studies and characterizations of products and feedstock materials should be taken place. In MSW management, the integration of various treatment techniques can provide sustainable solutions addressing different aspects and contamination levels. However, in moving towards a sustainable waste management approach, the integrated systems are essential to have preventive measures such as 3R, zero organic wastes ending up in landfills. The old landfills/dumpsites to be rehabilitated with improved technologies of biochar use (landfill covers), including constructed wetlands (phytocapping). Sometimes in catastrophic situations, organic wastes will end up in landfills, whereas incinerators may be needed to get rid of hazardous biological wastes.

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