Bulgarian Chemical Communications, Volume 57, Special Issue B (pp. 150-165) 2025 DOI: 10.34049/bcc.57.B.A0024

Transforming waste to wealth: biochar production from MSW for pollution mitigation and resource recovery

A. Kakkar[1], R. S. Gurjar[2], S. Kumar[3]*

[1]*Department of Chemistry, Banasthali Vidyapith, Tonk, Rajasthan-304022, India*
[2]*School of Automation, Banasthali Vidyapith, Tonk, Rajasthan-304022, India*
[3]*Department of Chemistry, DESM, NIE, National Council of Educational Research and Training, New Delhi-110016, India*

Revised: January 08, 2025

The rapid surge in waste generation worldwide is primarily fueled by population expansion. Open dumping of municipal solid waste (MSW) leads to significant environmental issues due to gaseous emissions and discharge of harmful substances from landfills. Biochar, a carbon-rich material derived from various biomasses, presents an opportunity to recover valuable resources and mitigate pollutants, thereby converting municipal solid waste into a valuable product. This article delves into producing biochar from waste materials, emphasizing that the techniques used for creating biochar from municipal solid waste can yield materials with a broad spectrum of characteristics. The article explores the potential uses of biochar, such as application as a permeable reactive obstacle to decrease pollution and as an eco-friendly absorbent for treating leachate. Likewise, biochar can serve as a covering material to diminish unpleasant odors. The generation process of biochar from waste materials is thoroughly discussed, highlighting the diverse material properties that can result from various methods employed for its creation. Additionally, the article examines the multiple functionalities of biochar, ranging from mitigating pollution as a permeable reactive barrier (PRB) and eco-friendly adsorbent for leachate treatment to its role as an effective covering material for odor reduction.

Keywords: Biomass, waste, biochar, municipal, material
Abbreviations: MSW-Municipal solid waste; AC-Activated carbon; IC-Inorganic contaminant; OC-Organic contaminant

INTRODUCTION

The increasing urbanization and industrialization rates heavily demand substantial energy consumption, often at the cost of environmental well-being. The global population of 8 billion is expected to soar to 8.5 billion in the upcoming years. The world was expected to make 2.3 billion tons of solid waste in 2020, which is about 0.79 kg of waste generated per person per day [1]. As cities and populations grow quickly, the amount of trash made each year is expected to increase by more than 70% from 2020 to 2050, reaching 3.88 billion tons. MSW demands urgent attention for proper management. Fig. 1 demonstrates the percentages of different materials found in MSW. In many regions, open dumping remains the predominant method for managing MSW despite the growing interest in more sustainable alternatives like composting and vermicomposting, primarily due to their relatively lower costs [2]. Moreover, highly toxic sulfide gas is generated in the composting method. Nonbiodegradable wastes with low moisture content, referred to as low-moisture urban garbage, are ideal for incineration. However, waste's high costs and moisture content restrict the widespread application of incineration, particularly in developing nations, especially those within the tropical belt with high yearly rainfall. However, incineration offers many benefits over landfill disposal, including a substantial volume reduction under relatively limited space, its implementation is constrained. The fly ash generated from the incineration of MSW serves as a significant contributor to pollution. Incineration can also lead to the formation of hazardous dioxins [3]. Solid waste management in underdeveloped nations accounts for a significant portion (20–50%) of local governing bodies' budgets [4, 5]. Astonishingly, this waste is generated by less than 50% of the city's population. In economically developed nations, MSW is considered an asset utilized for the production of the source of energy, which includes the generation of heat, primarily through pyrolysis and gasification processes [6]. Open dumping, prevalent in lower- and middle-income countries, releases a spectrum of environmental toxins into the environment, includ-

* To whom all correspondence should be sent:
E-mail: *sudeshneyol@gmail.com)*

ing CO_2, CH_4, N_2O, and acetic acid, classified as greenhouse gases, volatile organic compounds (VOC), potentially hazardous elements, and persistent organic contaminants [7].

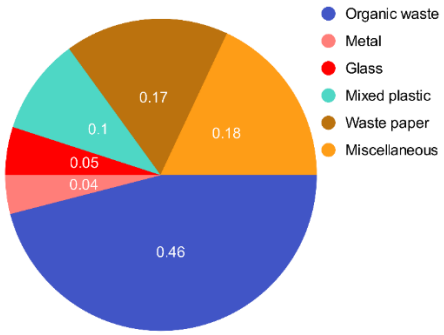

Fig. 1. Percentages of different materials found in MSW

Methane gas emission from open landfills significantly contributes to climate change, while these dumps frequently contain noxious substances like benzene, ethylbenzene, xylene, and toluene. The leachate from these dumps contains highly toxic substances, impacting various organisms and demonstrating increased transport capacity of trace metals like Cd, Ni, Hg, Cu, Mn, Pb, and Zn. Treatment of landfilled leachates poses a significant challenge due to their complexity [8]. A major global challenge remains in finding practical solutions to address the pollution from MSW. The development of efficient waste management systems must align with the reliability, quantity, and content of collected waste in specific areas. Anthropogenic factors, for instance, an absence of favorable attitudes regarding waste management, pose hurdles in establishing sustainable waste management systems due to the intricate nature of the problem, variability in waste sources, technological limitations, and scarcity of information flow. One potential solution involves the transformation of municipal waste into biochar and biogas through pyrolysis, representing a direct waste-to-energy process. The emerging trend of material recovery from debris involves utilizing biochar to achieve sustainable economic objectives. Biochar, distinguished for its exceptional adsorption properties, has found relevance in material science, leading to cleaner water and healthier soil [9]. Both pre-treatment of biomass feedstock and modification of biochar influence the characteristics of biochar. The presence of functional groups such as carboxylic acid, ketone, and hydroxyl along with the aromaticity in biochar derived from MSW facilitates the adsorption of contaminants *via* various mechanisms including surface coordination, electrostatic interaction, pi bonding, ion exchange, and hydrogen interaction. By converting raw waste into biochar, there is a significant reduction in waste production, rendering the process more environmentally friendly due to reduced energy consumption. The transformation of municipal waste into biochar, as shown in Fig. 2, usable as an adsorbent or soil amendment, holds promise in alleviating the mounting global waste burden. Utilizing biochar derived from municipal waste for wastewater purification, leachate treatment, and soil enhancement through nitrogen recovery [10] forms the focal point of this concise overview.

BIOCHAR FROM MUNICIPAL SOLID TRASH

Technologies

Resource recovery processes for MSW can primarily be categorized into biological and thermochemical methods (Fig. 3). The thermochemical accumulation of biomass is a pivotal process technology employed for the production of biochar within the temperature range of 200–900°C. This process encompasses three primary thermochemical techniques, namely pyrolysis, carbonization, and gasification, as illustrated in Fig. 4. The selection of specific process conditions is contingent upon various factors, including the biomass sources, their pre-carbonization treatment, and the intended main

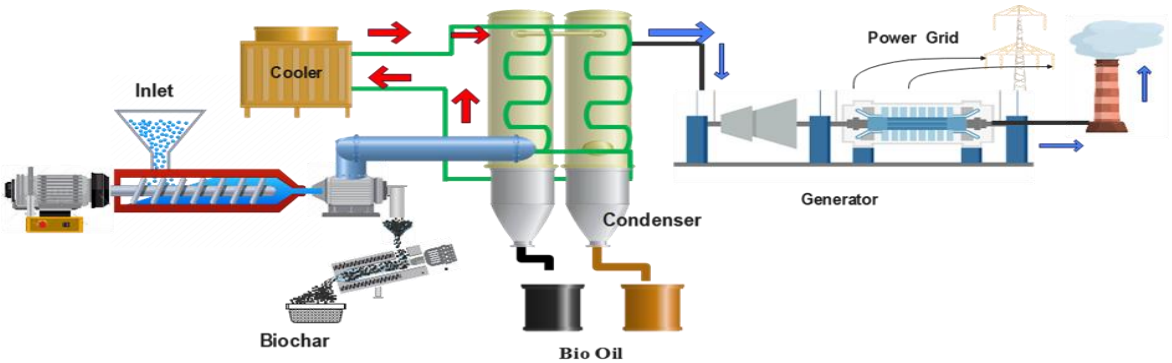

Fig. 2. Layout of the process of biomass conversion into various useful products

product, be it bio-oil, biochar, or energy. Pyrolytic transformation has emerged as a proven and effective method for converting biomass to mitigate contaminants [11]. Biochar's ability to remove organic and inorganic contaminants from soil and water environments is susceptible to the feedstock and pyrolysis conditions under which it was produced. These factors profoundly affect the physicochemical processes that determine the bioavailability of infection in certain ecological settings. Among the various pyrolysis techniques, gentle pyrolysis with low speed is among the most commonly utilized methods for biochar production. Slow pyrolysis features a slow rate of heating (typically less than 10 °C/min) and extends for a duration ranging from minutes to several hours [12]. This method yields a substantial amount of biochar, often reaching up to 35% of the original biomass. Conversely, fast pyrolysis, characterized by a high heating cycle (~1000°C/s), results in a lower biochar production (around 10%) while primarily generating bio-oil as its principal product (approximately 70%) [13]. Torrefaction, another pyrolysis process, operates at lower temperatures (190–281 °C) and leads to the partial accumulation of biomass [14, 15]. In MSW, numerous research studies have concentrated on low to moderate mode of pyrolysis methods for its management. On the other hand, fast pyrolysis of MSW is also gaining attention. Notably, the reported biochar generated from numerous researches exhibits a broad range, from 15% to 65%, reflecting the diversity and complexity of factors influencing the biochar production process. The principal method for generating biochar from MSW involves pyrolysis of biomass, as shown in Fig. 5. Within this domain, slow pyrolysis is conducted at temperatures between 390–600°C to maximize biochar yield; bio-oil, C1–C2 hydrocarbons, and syngas are generated by-products. Results are susceptible to reaction parameters and the specifics of the used agricultural waste. In contrast, hydrothermal carbonization is a viable method for biochar production in regions characterized by wet, humid atmospheres or surroundings, where MSWs possess substantial moisture content [16]. This method reduces the energy required for drying, decreasing the overall price and power required for biochar production compared to conventional pyrolysis techniques. However, it is important to note that the surface area obtained by hydrothermal carbonization tends to be less than by other pyrolysis techniques [17]. Existing MSW biochar manufacture studies have mostly been conducted at small or laboratory scales. Scaling up the production to a larger, industrial scale, targeting a given quality is challenging due to MSW feedstocks' dense and amalgamated nature. The diverse nature of these feedstocks poses a challenge in designing an effective large-scale production process that meets specific criteria.

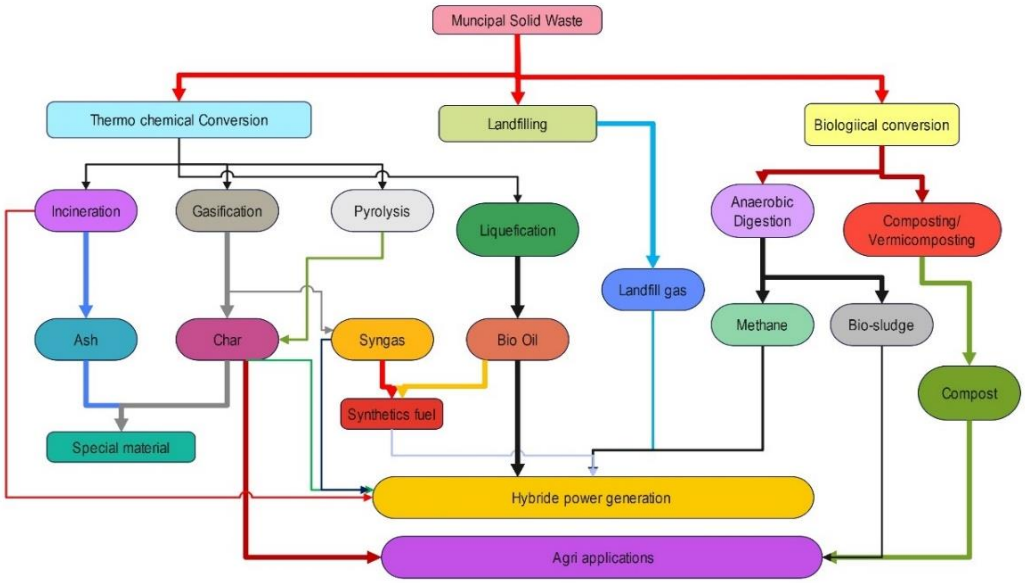

Fig. 3. Different techniques for MSW conversion

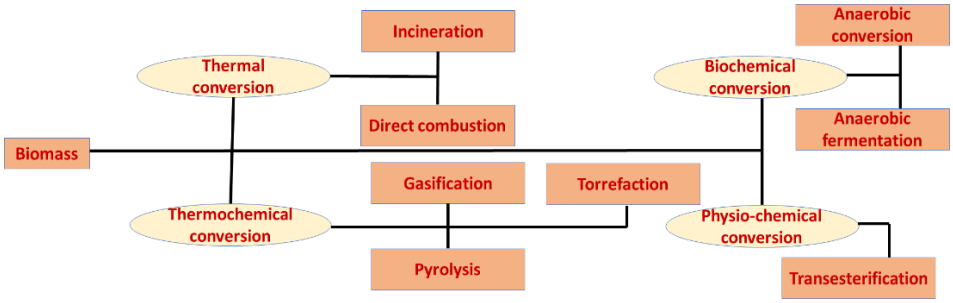

Fig. 4. Conversion of urban biowaste into biofuels, gaseous products, and carbon-rich solids. Torrefaction and gasification are mostly used to pretreat biomasses before combustion, not to make MSW biochar.

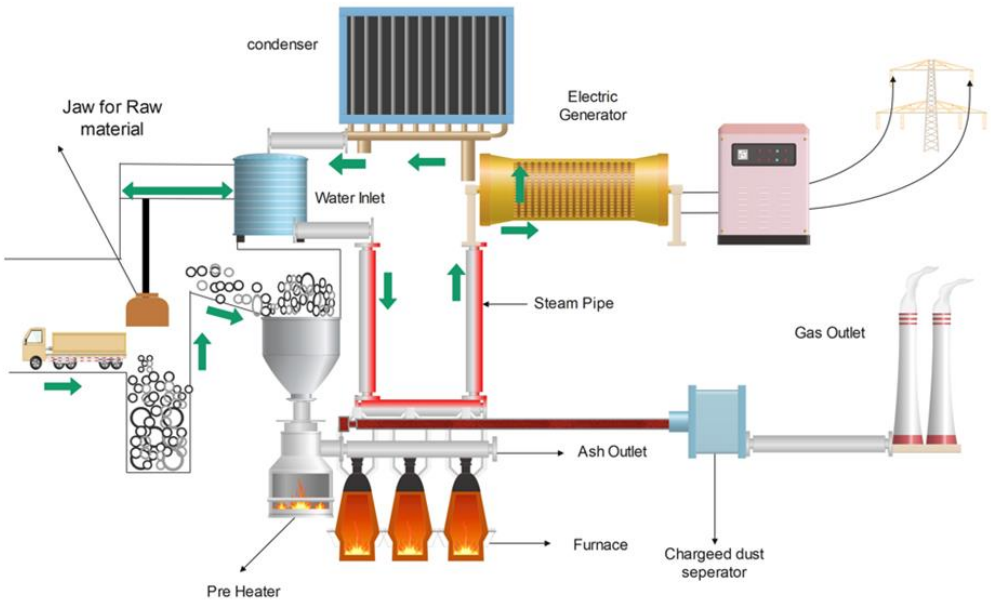

Fig. 5. Pyrolysis of biomass

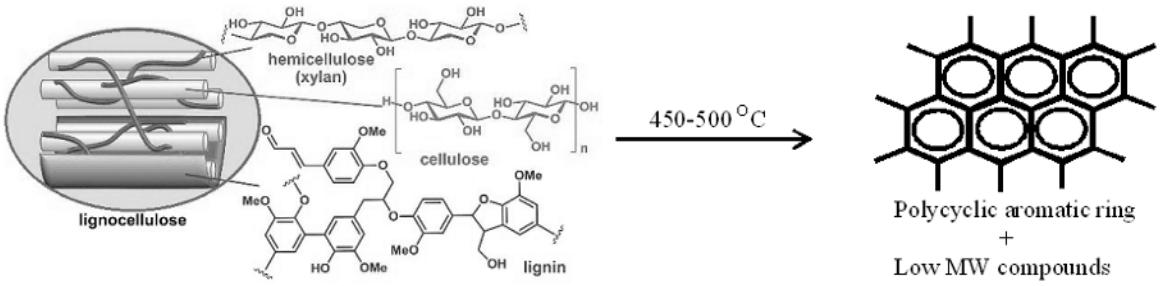

Fig. 6. Biochar formation [18] (open access, no copyright permission required)

Biomass pyrolysis occurs through 3 fundamental steps:

(1) *Evaporation:* At 100°C, the biomass releases moisture content and forms amorphous carbon, which is used for biochar production.

(2) *Biochar production:* Biochar is an aromatic polycyclic molecule formed during the pyrolysis process of biomass. Since primary biochar easily breaks down into secondary biochar, water, and gas, it acts as a catalyst for secondary reactions. So, it must be quickly removed. As a result, the yield of bio-oil declines. The synthesis of benzene rings and their coupling with polycyclic compounds constitute the primary route of this reaction. The formation of biochar from biomass is shown in Fig. 6.

(3) *Depolymerization:* The depolymerization procedure breaks down the lignocellulosic polymer bonds yielding smaller monomers and saturated substances of low molecular mass at temperatures ranging from 300 to 450 °C. This causes chain formation and produces volatile compounds that condense to liquids at room temperature.

(4) *Disintegration:* This process involves the covalent bonding between the monomeric units,

which produces small straight-chain chain molecules and noncondensable gases. Cellulosic biomass undergoes decomposition into alcohols, carbonyl acids, and other compounds at a temperature of about 600 °C. This process is depicted in Fig. 7.

(5) *Secondary processes*: At the operating temperature of the furnace, volatile substances are not persistent when produced during the depolymerization and disintegration process; instead, they further undergo secondary processes which include cracking and repolymerization. The process of cracking involves the breakdown of bonds of volatile substances and the creation of molecules with high weight. Large polycyclic hydrocarbons, which are occasionally stable at the operating temperature of the furnace, are created when volatile substances recombine in repolymerization reactions. The reaction processes for biomass pyrolysis are shown in Fig. 8.

Properties of MSW-derived biochar

The summary from Table 1 underscores the considerable variability in the properties of MSW biochar, emphasizing the impact of different processing conditions, feedstock composition, and methodologies used in the production process. The correlation between pyrolysis temperature and the resulting surface area indicates a trend that could provide insights into optimizing biochar production for specific applications or desired properties.

APPLICATIONS OF BIOCHAR

Biochar as a green adsorbent

Due to its promising results in reducing the concentrations of numerous pollutants, including heavy metals, contaminants, and other nutrients, biochar has been the subject of extensive research and widespread interest. Among the diverse ranges of feedstocks used for biochar production, MSW has recently emerged as a focal point in waste management strategies. Several studies have highlighted the application of biochar synthesis from MSW as a dual-purpose solution [19].

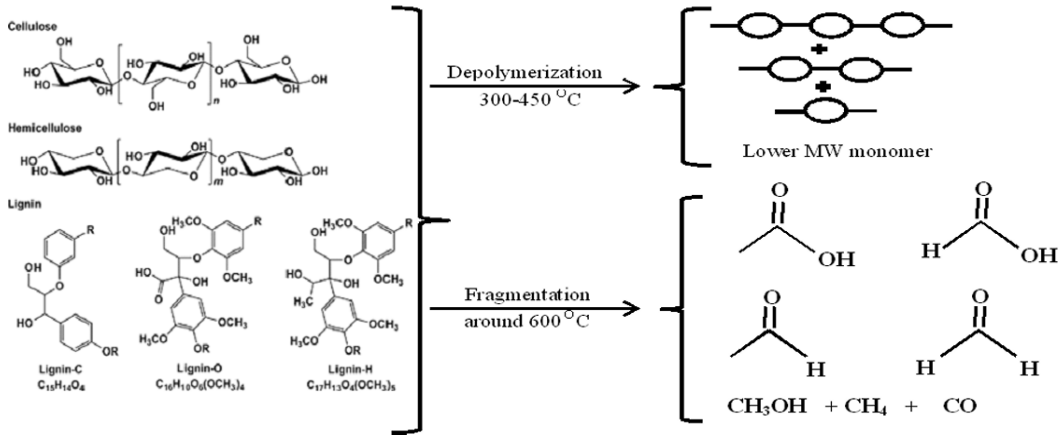

Fig. 7. Depolymerization and disintegration process in pyrolysis [18] (open access)

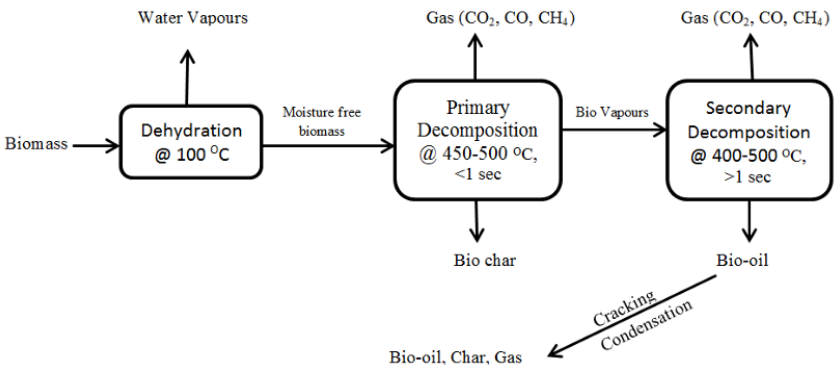

Fig. 8. Reaction processes for biomass pyrolysis [18] (open access)

Table 1. Main properties of the biochar pyrolyzed at different temperatures

Country	Process	Temp Zone *(°C)*	Volatile matter *(%)*	Ash *(%)*	Fixed material *(%)*	% (of N, C, O, H)				Surface area m^2/g	Pore volume cm^3/g	Ref.
China	SP	D	67.9	74.2	--	1.54	17.4	10.4	0.7	--	--	[20]
		E	73.7	77.9	--	1.38	18.4	7.3	0.34	--	--	
		F	78.6	81.5	--	0.95	16.92	6.8	0.21	--	--	
India *(Agri-culture)*	SP	D1	64.2	18.1	--	3.39	74.37	--	2.21	--	--	[21]
Sri Lanka	SP	C	30.1	15.6	46.5	1.33	60.8	14.6	2.79	212.9	0.013	[22]
Australia	SP	C	11.9	72.7	13	6.09	68.2	20.1	4.33	--	--	[23]
		D	8.5	76.5	12.6	5.79	76.7	13.6	2.84	--	--	
			6.3	76.8	14.3	6	80.7	10	2.64	--	--	
USA *(Mixed material)*	SP	C	--	6.1	65.2	1.3	48.6	31.4	12.2	20.7	--	[24]
		D	--	9.2	63.8	1.4	59.5	20.8	9.1	29.1	--	
		E	--	6.2	78.2	1.3	70.1	13.7	8.4	29.8	--	
	SP	C	21.9	6.4	71.7	1	76.8	12.5	3.3	359.8	0.14	[25]
		E	9.4	7.9	83.6	1	83.8	6	1.2	380.9	0.15	
South-Korea	Hydro-thermal carboni-zation	A	74.2	12.5	13.3	0.4	41.7	40.1	5.3	--	--	[26]
Qatar *(Hard, Soft, Paper, Mixed material) (P2, P4, P6 at 2, 4, 6 h time span)*	P1	B	--	10.1	--	0.3	40.7	53.6	5.2	--	--	[27]
		D	--	20.5	--	0.7	51.7	45.8	1.7	--	--	
		F1	--	20.6	--	0.5	61.2	38.3	0.01	--	--	
	P2	B	--	10.3	--	0.6	45.6	49.7	4.6	--	--	
		D	--	20.5	--	0.6	56.3	41.3	1.9	10	--	
		F1	--	30.2	--	0.5	62.5	37	0	5	--	
	P3	B	--	10.5	--	0.6	48.2	46.6	4.5	140	--	
		D	--	20.5	--	0.8	55.2	42.5	1	155	--	
		F1		30.1	--	0.5	60.5	38.9	0.1	160	--	
Canada	SP	C	--	--	--	2.7	19.2	12.7	1.3	--	--	[28]
		C1	--	--	--	2.6	18.6	11.9	1	--	--	
		D	--	--	--	2.4	17.2	10.9	0.8	--	--	
		D1	--	--	--	2.1	15.2	9.2	0.6	--	--	
	SP	D	18.45	18.6	61.13	5.97	60.7	31.24	2.01	--	--	[29]
		D1	17.51	21.35	60.2	6.57	66.1	23.8	2.84	--	--	
Spain	SP	C	--	--	--	1.3	30.1	6.8	1.6	--	--	[30]
		D	--	--	--	1.3	28.8	5.5	1.2	--	--	
		F	--	--	--	1	28	1.9	0.7	--	--	
UK	SP	C	--	--	--	1	47.2	5.7	0.8	--	--	[31]
Brazil	SP	B	--	--	--	3.17	24.3	75.23	1.73	--	--	[32]
		D	--	--	--	2.9	20.99	70.7	0.88	--	--	

Note: Slow pyrolysis-SP, Pyrolysis- P, Not Available-NA, Nitrogen-N, Oxygen-O, Hydrogen-H, Carbon-C
Temperature range *°C (A-200-299, B-300-399, C-400-449, C1-450-499, D-500-549, D1- 550-599, E-600-699, F-700-749,F1-750-799*

Table 2. Potential application of biochar for mitigation of inorganic and organic contaminants

Biomass source	Temperature (°C)	Medium	Pollutant	Type of contaminant	Ref.
Green biomass	450	Water	Atrazine	OC	[33]
Hard wood	400	Soil	Arsenic	IC	[34]
Cotton straw	850	Water	Chlorpyrifos and fipronil	OC	[35]
Rice straw	700	Soil	Pentachlorophenol	OC	[36]
Soybean	700	Water	Mercury	IC	[37]

Note: OC-Organic contaminant; IC-Inorganic contaminant

Table 3. Average yields of biochar at various pyrolysis temperatures and residence times [40]

Pyro temperature (°C)	Duration (min)	Yield (%)				
		BC	BC-K (1)	BC-K (0.5)	BC-P (1)	BC-P (0.5)
300	30	62.5	47.7	60.5	62.9	53.9
400	30	28.5	37.4	35.1	48.9	48.4
500	30	27.3	27.2	31.7	36.9	39.3
300	60	58.1	47.2	51.1	55.1	65.7
400	60	25.5	30	28.2	45.6	42.2
500	60	27	21.5	28.9	34.5	35.4
300	90	64.2	42.6	32.9	57.1	59.8
400	90	27.5	33.6	28.7	40.8	41
500	90	31	25.9	25.5	34.4	37

The multifaceted applications of MSW-derived biochar have shown promising outcomes, particularly in treating leachate, constructing permeable reactive membranes, and capping landfills. These applications have displayed effective results in addressing environmental pollution challenges. Table 2 presents an overview of various biochar feedstocks and their potential for mitigating organic and inorganic contaminants. Studies have also delved into the efficacy of biochar in soil applications, demonstrating its ability to supply and retain nutrients beneficial for plant uptake. Notably, biochar exhibits the potential to retain bioavailable nutrients in the soil over prolonged periods, thereby contributing to enhanced soil fertility and plant growth.

In Table 3, the amount of biochar that can be synthesized at various pyrolysis temperatures and residence times, is indicated by the information that has been provided. Interestingly, the increase in residence duration did not influence the biochar yield. No substantial variations were observed among samples subjected to pyrolysis temperatures for 30, 60, and 90 min. This suggests that pyrolysis reactions reached completion within the initial 30-min period, indicating no significant benefit in extending the pyrolysis duration beyond this timeframe. Therefore, conducting pyrolysis for a longer duration is unnecessary, as the reactions seem to be fully realized within 30 min of the process. Since the majority of the biomass's active sites have already been occupied, increasing the residence time does not increase the breakdown of biomass [38]. Secondary processes like gradual carbonization of tars or thermal cracking of volatile substances may take place during prolonged residence times. The quality and composition of the biochar are mostly impacted by these processes and not the total yield [39].

An increase in the temperature of the pyrolysis process resulted in a significant reduction in the amount of biochar produced. For instance, when the pyrolysis temperature was raised, there was a significant reduction in the amount of biochar (BC) that was produced. The yield was measured as 62.5 % of the dry feed mass when the temperature was 300°C, but when the temperature was 400°C , the yield dropped to 28.5 %. The amount of biochar produced by BC, BC-K(0.5), BC-K(1), BC-P(0.5), and BC-P(1) decreased by 34.9 %, 27.9 %, 21.1 %, 13.9 %, and 19.8 %, respectively, as the temperature increased from 300 to 500°C. This decline in amount of biochar produced is probably related to additional pyrolytic transformation, which suggests that the original feedstock underwent a more thorough primary breakdown or that secondary reactions of the solid residue took place [41]. The reduction in biochar yield with increasing pyrolysis temperature

signifies a shift towards a more complete conversion of the original biomass material, resulting in a lower proportion of biochar in the final product. The trend of decreasing biochar yield with an increase in pyrolysis temperature has been noted by numerous researchers. For instance, Kim & Parker observed a 34% reduction in the amount of biochar when the thermal decomposition temperature of digested sludge was escalated from 250 to 500°C. This pattern aligns with the broader trend observed in various studies, where higher pyrolysis temperatures often result in a diminished yield of biochar [42], while Shen & Zhang found comparable results [43]. Hossain observed the biochar generation through pyrolysis of sewage sludge in a fixed-bed reactor. He noted that at a temperature of 300°C, the biochar accounted for 72.3% of the initial mass [44]. However, as the pyrolysis temperature was increased to 700°C, the biochar yield decreased significantly to 52.4%. This observation reaffirms the common trend in pyrolysis processes, where a rise in pyrolytic temperature correlates with a reduction in the amount of biochar.

The chemical impregnation of sewage sludge exhibited a minimal impact on biochar yield produced at 300°C. Interestingly, the presence of H_3PO_4 resulted in a decrease in the weight reduction rate from 300-500°C. Specifically, at the temperature of 500°C, the biochar amount of BC-P(0.5) was measured as 39.3%, which was notably higher than other biochar samples averaging approximately 30% at the same temperature. Furthermore, the increase in the impregnation ratio from 0.5 to 1 did not affect the biochar yield [42].

Similarly, Lim *et al*. examined activated carbon (AC) production from palm shells and noted that the chemical impregnation ratio did not influence the yield of the solid product [45]. This suggests that in certain cases, variations in impregnation ratios or the presence of specific chemicals during the pyrolysis process may not significantly impact the biochar output but this primarily controlled the sorption capacity and specific surface area of AC [46].

Leachate treatment

Leachate, which is a water-based solution that comes from open dump sites, is full of different kinds of contaminants that are formed when waste degrades in landfills [47]. The organic constituents of leachate change based on factors such as type of waste present, duration of landfill operation, and prevailing weather patterns. Leachate from landfills typically contains significant quantities of pollutants, with around 80 to 95 % being inorganic and 52% as organic. Thus, any treatment method employed should possess the capability to extract highly toxic elements, such as zinc, mercury, nickel, Cd, Mn, Cu, and Pb, that have significant concerns associated with these leachates. Biochar, in general, has showcased remarkable efficiency in the removal of possibly hazardous elements from both soil and aqueous sources. The distinct blackish coloration of landfill leachate is attributed to the abundance of organic matter (OM), particularly rich in humic and fulvic acids [48]. Additionally, leachate stemming from MSW dumps contains persistent organic pollutants and volatile organic compounds. Biochar exhibits a favorable ability as a material for eliminating these highly noxious compounds. In the domain of leachate treatment, biochar serves as an effective adsorptive for the removal of harmful components like NH_3–N, colorants, hazardous metals, and chemical oxygen demand (COD) [49]. Traditional leachate method often falls short in meeting discharge requirements, where biochar emerges as a supplement due to its small, low-volume pores and high surface area, facilitating adsorption and chemical reactions within the treatment process. The superior functionality of biochar to eliminate a diverse array of biodegradable and non-biodegradable pollutants dissolved in a water medium is attributed to its microporous structure, thermal stability, and expansive surface area. However, despite its efficacy, the high production cost and expensive nature of carbonaceous substances stand as restricting different aspects in the widespread utilization of biochar for leachate treatment. Addressing the challenges associated with the production cost of biochar for leachate treatment can be achieved by utilizing in the vicinity accessible, economical resources such as industrial by-products and agri and food residue [50]. This approach holds the potential for reducing production expenses and enhancing the feasibility of implementing biochar for effective leachate treatment. Further analysis of biochar derived from MSW revealed minimal traces of metals. However, these trace amounts were not significant enough to hinder its efficacy or use as an adsorbent. This finding underscores the promise of biochar as an effective adsorbent for removing hazardous gases from landfill sites without posing significant constraints on the environment [51]. This demonstrates the potential of biochar derived from MSW as a viable and environmentally friendly solution for addressing leachate-related issues. Due to their cost efficiency, biological methods are employed for the removal of organic pollutants. Nonetheless, these methods can not effectively eliminate toxic metals from leachate. The bioreactor

treatment method is categorized into aerobic and anaerobic processes. The primary limitations of the biological method relate to the challenges with temperature regulation and the toxic effects of leachate on microorganisms. Anaerobic membrane bioreactors typically exhibit superior activity in treating leachate compared to aerobic methods due to the elevated COD levels of leachate. Along with biological methods, advanced oxidation methods i.e., Fenton reactions, electro-oxidation, and photocatalytic processes are also effective for the breakdown of various contaminants in leachate. The anaerobic membrane bioreactor for landfill leachate is shown in Fig. 9.

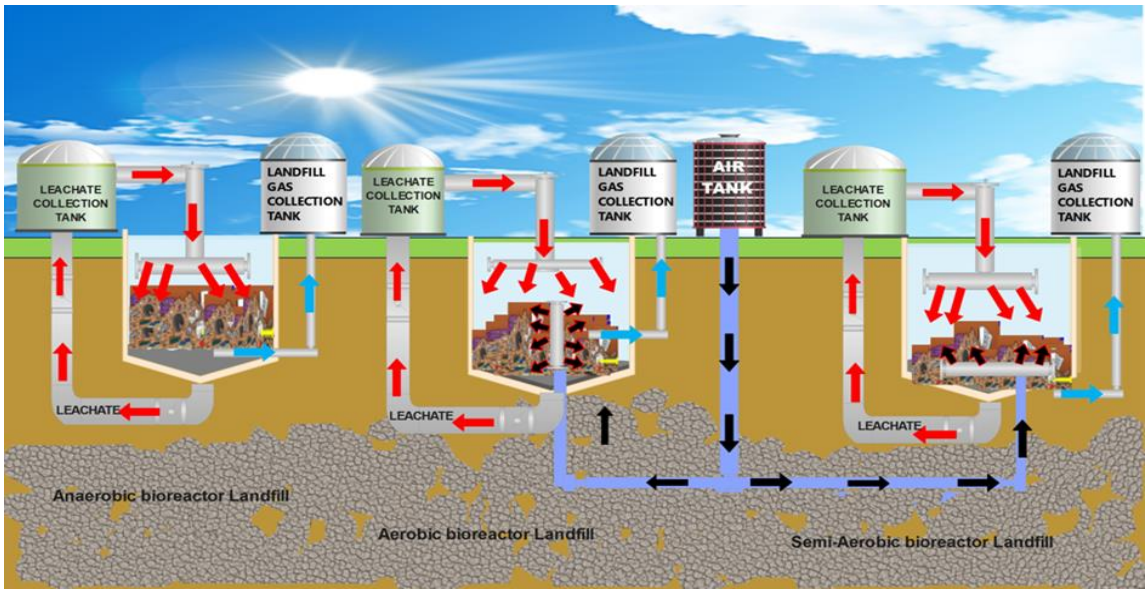

Fig. 9. Anaerobic bioreactor for landfill leachate treatment [52]

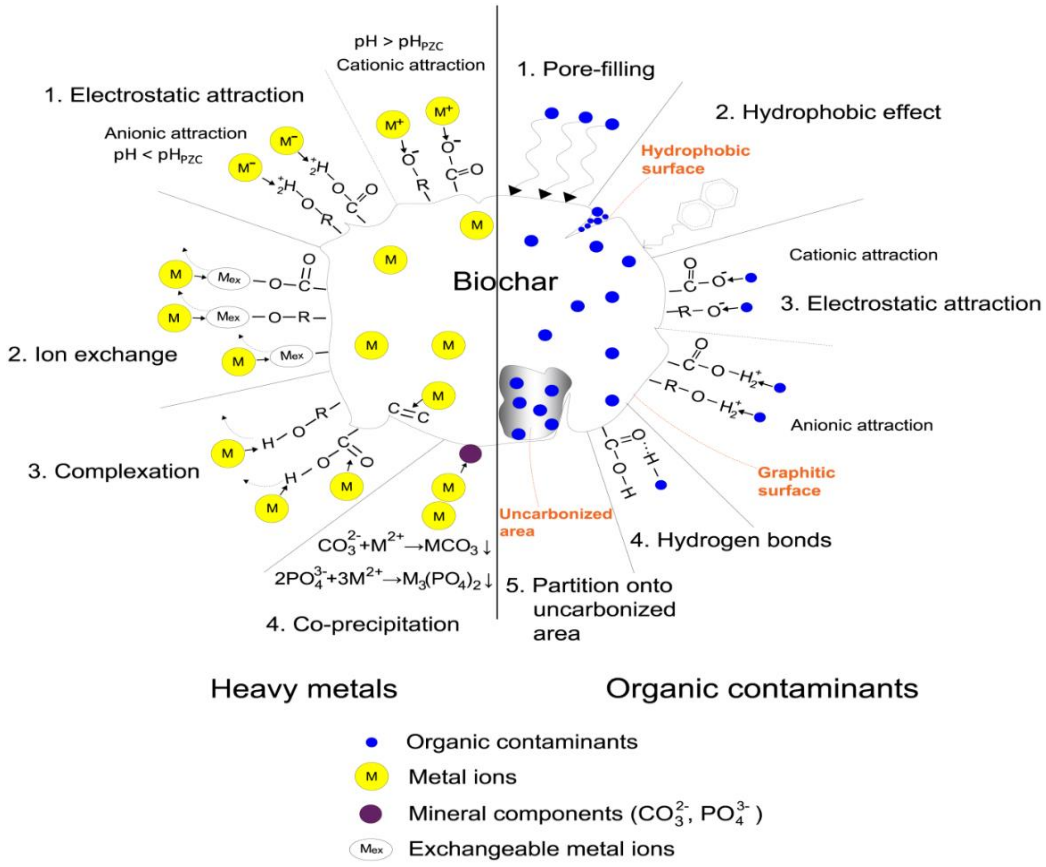

Fig. 10. Methods involved in the use of biochar to remove organic contaminants and heavy metals [59] (open access)

Heavy metal ion adsorption

Permeable reactive barriers (PRBs) are subsurface constructions designed to intercept and remove contaminants from groundwater before they enter water streams. Historically, AC and zero-valent iron have been the primary materials used in PRBs due to their effective contaminant adsorption capabilities, despite the high production cost of zero-valent iron hindering its broader use [53]. As a more cost-effective alternative, biochar has shown promising results in this field. Recent research has shown that using modified corn straw biochar as a PRB material is an effective way to prevent vanadium transport in subsurface environments. It demonstrates a three to five times greater capacity for removal than AC [54]. In contrast, biochar made from wood showed a relatively short lifespan as a potential PRB material for sites contaminated with e-waste when it was tested in column experiments [55]. In contrast, the incorporation of biochar made from coconut shells showed promising results in the elimination of lead (Pb) and cadmium (Cd) [56]. Biochar produced from MSW has been investigated for its ability to remove a variety of potentially hazardous elements, including arsenic (As) and chromium (Cr) in both the III and the VI oxidation state (As (III), As (VI), Cr (III), and Cr (VI)) [57, 58]. According to a number of studies, the amount of arsenic that can be adsorbed by biochar made from coconut husks is significantly lower than the amount of arsenic that can be adsorbed by biochar made from MSW, which shows that adsorption is 1.3 times higher [24]. The main processes using biochar to remove organic pollutants and heavy metals are depicted in Fig. 10. Balanced ion exchange, surface precipitation, electrostatic pull, complexation, and surface absorption are the processes that cause inorganic contaminants to adsorb on biochar. In this regard, a number of variables such as basicity, hydrophobicity, ion transfer capacity, and chemical composition, affect biochar's adsorptive properties. The absorption capability of biochar can also be changed by surface reactivity. Additionally, complexation occurs by the exchange of cations as a result of metallic ions replacing positive charge on the biochar surface. On the contrary, a number of distinct interactions can also be linked to the elimination of organic pollutants. Pore-filling, hydrophobic, electron donor and acceptor, partitioning, and electrostatic forces are the most common types of interactions [59]. Based on the literature that is currently available, electrostatic attraction is proposed as a likely mechanism for heavy metal adsorption onto MSW biochar. However, research on MSW biochar is still limited, particularly in characterizing its mineral and organic phases concerning pyrolysis temperature. It has been discovered that the quantities of polycyclic aromatic hydrocarbons and possibly hazardous elements in biochar produced from MSW are low and still within permissible limits. However, it is essential to take into consideration its derivatives, as well as the high concentrations of phenolic compounds that were discovered. More in-depth investigation and comprehension of these components are necessary to perform an exhaustive analysis of their applicability across a variety of contexts.

Material for landfill capping

Both the elimination of emissions of greenhouse gases and the control of offensive odors continue to be difficult problems to solve in the field of landfill management. To address these concerns, a number of different strategies have been implemented, including gas-accumulation systems [60], compacted clay [61], and composite covers [62]. Despite their initial efficacy, they have a number of drawbacks including shorter lifespans, susceptibility to cracking that can result in water percolation, and reduced methane oxidation as a result of limited oxygen-methane interaction. These drawbacks are compounded by the fact that compacted clay covers can crack easily. This has led to the development of biologically active coverings or filters as critical components of landfill gas mitigation infrastructure. Because of its useful properties, such as significant specific surface area and smaller particle sizes, biochar that is produced from MSW has garnered a lot of attention recently. Because of this property, the rate at which methane is oxidized is increased, and methanogenic microorganisms can interact more effectively with methane and oxygen [63]. In these kinds of situations, making use of biochar is not only beneficial in terms of its ability to effectively reduce pollution but also saves money by enabling the recycling of secondary resources. Biochar has found application in landfill cover engineering, leading to observed increases in CH_4 removal rates through oxidation as showin in Fig. 11, sometimes reaching up to 90% [64]. Additionally, Phyto-capping, a technique involving dense vegetation growth in the upper layer of soil, acting as a cover of the landfills, has been used to mitigate landfill gas emissions [65]. The presence of vegetation helps regulate water at waste disposal sites by absorbing surplus moisture through their root systems, thereby diminishing surface water flow and lowering the threat of leachate leakage. Plants absorb nutrients from the soil, aiding in the reduction of pollutants at waste disposal sites by assimilating and retaining them.

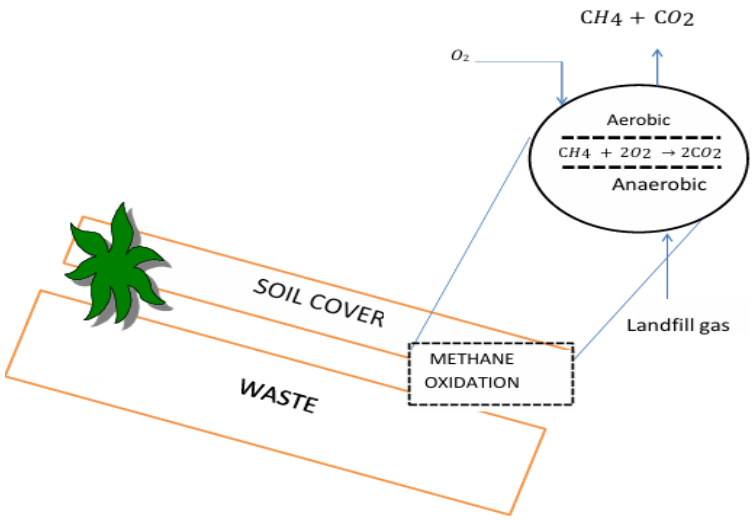

Fig. 11. Oxidation of mehane in landfill coverings [67] (open access)

Plants also encourage microbial metabolism, especially in the rhizosphere, where soil is impacted by root exudates and their associated microbes. These microorganisms can contribute to the decomposition of organic contaminants and improve soil structure. A significant drawback of phytocapping is its potential ineffectiveness in locations where evapotranspiration rates do not exceed precipitation levels, such as chilly and moist climates. Choosing plant varieties necessitates a thorough comprehension of location characteristics, local climatic trends, and soil characteristics specific to the area. There's also the potential for plants to reach buried debris, resulting in either their demise or the dispersion of pollutants into the surroundings, particularly if those chemicals are concentrated within the waste in greater amounts [66]. It's also important to ensure that the plant variants not only survive but also adapt to fluctuating arid and moist weather conditions, as well as endure associated challenges like vegetation fire. Studies have suggested that combining biochar with the soil layer can further enhance methane oxidation in this process. Ultimately, the integration of biochar into landfill management strategies shows promise in enhancing methane oxidation, reducing greenhouse gas emissions, and managing odors, presenting a cost-effective and environmentally friendly solution in mitigating pollutants emitted by landfills.

Retention and recovery of nutrients

Biochar made from MSW has been shown to improve soil quality because of its high organic carbon content [68]. This biochar has been shown to improve soil chemistry and biology. Soil mineralization has been found to shift after biochar synthesized from MSW was added, as a result of the biochar's extensive porous structure. Because of its improved structure, plants are better able to withstand damage from abiotic oxidants and microbial enzymes, and crop yields are raised as a result of less nutrient runoff and greater carbon sequestration. Additionally, biochar's sorbent properties enable the retention of additional nutrients from pesticides and fertilizers [69]. The incorporation of MSW-derived biochar into soils has been shown to improve soil pH, and cation exchange capacity, and directly contribute to enhanced plant growth, as shown in Fig. 12. The use of a mixed variation in feedstock biochar production significantly enhances soil buffering capacity, moistness, and water-holding capability. Moreover, several results show that trace metals in MSW-derived biochar are notably low, making it a viable option for soil application without further contamination. Biochar has also found utility as an additive to catalyze the composting process, enhancing aerobic conditions and facilitating complexation with anions and cations exchanged within the compost [70]. While trace metal concentrations in the biochar may form complexes with soils, these are generally insignificant and do not re-contaminate soils but instead facilitate retention rates. The pH modification and reduction potential changes brought about by the addition of biochar have been beneficial in neutralizing acidic soils and enhancing soil fertility, water retention, and nutrient availability, especially in arid and acidic soil conditions. Pyrolysis temperature and the organic and inorganic sources of the MSW used play significant roles in improving soil quality and catalyzing compost formation.

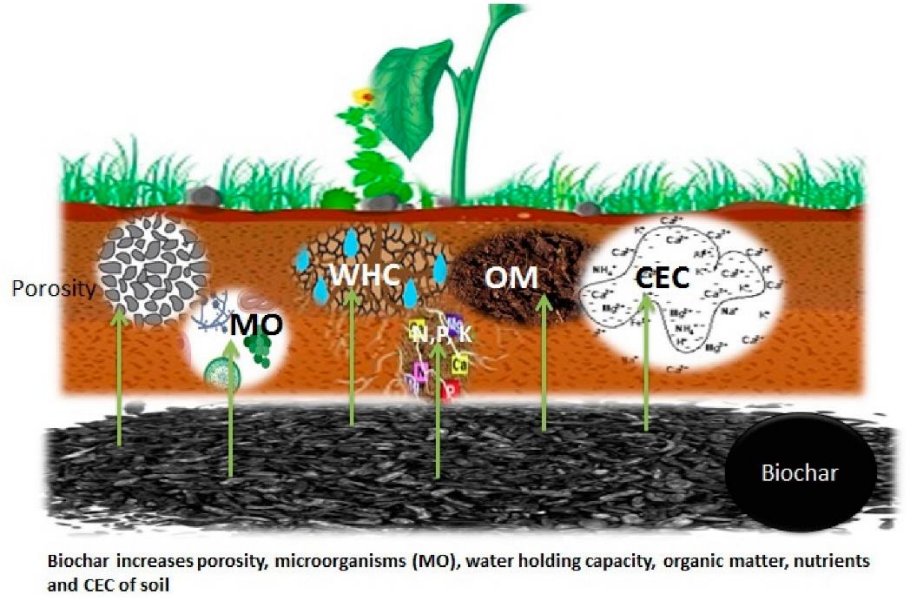

Fig. 12. Use of biochar on soil quality. WHC = water holding capacity; OM = organic matter; CEC = cation exchange capacity [71] (open access)

The nutrient value of biochar derived from biomass *via* pyrolysis depends on the type of biomass feedstock and the pyrolysis temperature. Elevated temperatures typically induce increased breakdown of organic substances present in the biomass. This can result in a low nutrient value of biochar. Biochar generated through low-temperature pyrolysis contains a high proportion of carbon derived from biomass. The combination of high carbon content, along with strong adsorption capacity, large surface area, and highly alkaline nature, renders the incorporation of biochar into the soil a viable and efficient method for improving soil fertility. The alkalinity of biochar, coupled with high carbon content, improves cation exchange capacity, resulting in increased capacity to adsorb toxic metals, thereby enhancing soil fertility. The efficacy of biochar in retaining and releasing nutrients is influenced by soil properties. Biochar enhances the capacity to retain nutrients and water but these properties are contingent not only on the type of biochar but also on the soil's ability to retain. Additionally, biochar helps crops by encouraging the growth of soil microbes and helping them retain water even in stressful situations. Its gradual release of nitrate has also been researched as a potential method for providing plants with continuous nutrient delivery. This slow release behavior, including the reduction in chemical fertilizer release rates, contributes to the sustainability of agronomic systems utilizing biochar synthesized from MSW.

CONVERSION OF BIOMASS INTO ENERGY

Biochar is produced as a by-product during the process of direct conversion of MSW into energy. To produce usable forms of energy from MSW, a number of different conversion processes, including thermal, biochemical, and physicochemical, are utilized. Direct combustion of dry biomass generates heat, serving basic purposes like cooking. Gasification, conducted at higher temperatures (680–1500°C) and lower pressure with limited or no oxygen, results in the production of a gas mixture called syngas, containing H_2, CO, CH_4, and CO_2 (Fig. 13) [72]. Challenges in storing and maintaining syngas due to high associated costs are notable. Additionally, the formation of coke and tar substances during gasification can cause fouling in gasifier chambers. On the other hand, due to the high organic content and calorific value that it contains, MSW is an excellent candidate for the production of gas and liquid fuels at a cost that is significantly lower than it would be otherwise [73].

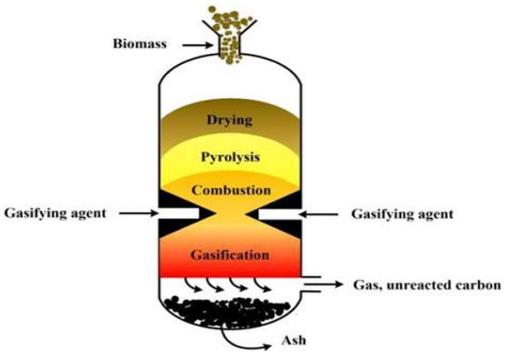

Fig. 13. Gasification of biomass [74] (open access)

Pyrolysis, conducted in limited or no oxygen environments, prevents the generation of toxic air pollutants like dioxins. This process is made more efficient by focusing on the organic materials from MSW.

Torrefaction is a thermochemical process that produces homogeneous densified pellets with properties that are comparable to those of coal. Torrefaction is conducted at temperatures between 200 and 300°C at a slower heating rate [75]. As a high-quality fuel for small-scale combustion, entrained flow gasification, and power plants, these pellets are an invaluable resource because up to 96% of the energy they produce is hydrophobic and resistant to biodegradation. Importantly, it's not just waste that generates biochar; biochar itself can serve as an energy source in various methods, contributing to the overall sustainable management of resources and waste materials.

CHALLENGES AND FUTURE DIRECTIONS

Although biochar made from MSW has a lot of uses, its drawbacks must be recognized and addressed for its efficient usage. The varied composition and quality of biochar obtained from MSW is one of its major drawbacks. MSW is made up of a variety of materials with distinct properties, such as paper, plastics, and organic remains. The characteristics and functionality of the final biochar can be impacted by this diversity. If impurities like toxic metals or organic contaminants are present in the substrates, they can be harmful to the environment if not appropriately controlled. Thus, to guarantee the efficacy and safety of biochar, thorough feedstock selection and strict quality control procedures are crucial. Another drawback is that improper usage or management of biochar can have detrimental effects on the ecosystem. For instance, excessive application of biochar or failure to take into account the particular soil conditions may result in unforeseen impacts like diminished bacterial activity, pH changes, or mineral imbalances. Furthermore, poor handling or removal of biochar scraps following use may cause land deterioration or environment pollution. To reduce the dangers and optimize the advantages of biochar, appropriate regulations and efficient procedures for management are required. Manufacturing and employing of biochar made from MSW on a big scale might be difficult in terms of profitability and scalability. Broad implementation may be hampered by variables including large upfront costs, the requirement for cutting-edge technology, and the creation of suitable logistics systems. In addition, to guarantee the financial viability of biochar programs, consumer demand, legal frameworks, and financial factors must be thoroughly assessed. More study and research are required to completely comprehend the long-lasting consequences and advantages of biochar made from MSW in various uses and settings [76]. Additional research is required to evaluate its effectiveness, longevity, and possible interactions with different soil kinds. For a thorough assessment of the environmental impact of biochar manufacturing, it is also essential to evaluate the net ecological and greenhouse gas (GHG) release consequences of the process, particularly the energy inputs involved. Biochar derived from MSW exhibits the potential to promote the worldwide sustainability goals through efficient waste management, encouraging environmentally friendly production and use, reducing global warming, and aiding in the preservation of land. For the more widespread use of biochar towards sustainable growth globally, more innovations in technology and governmental support are required.

CONCLUSION

The lack of sustainable waste management practices, which increases the risk to human health and environmental degradation, is the main reason why the rise in waste generation has become a global concern. Multifaceted approaches are needed to address this problem, and biochar—which is made from MSW—offers a creative and promising one. The method uses, and prospects of biochar as an environmentally friendly waste management option have all been covered in this article. Biochar offers a wide array of potential uses in waste management, like as an effective material for environmental remediation, an adsorbent for pollutant mitigation, and leachate treatment. Different thermochemical methods like slow pyrolysis, torrefaction, and pyrolysis, are used in the production process, and each influences the characteristics and yield of biochar [77]. These techniques provide different material qualities which affect the possible uses of biochar. By using biochar made from MSW, waste volumes can be decreased while maintaining a greener approach and a significant reduction in energy consumption. It is a versatile solution due to its effectiveness in eliminating hazardous substances from leachate treatment and its potential application in building PRBs for the removal of groundwater contaminants. Additionally, by promoting composting, boosting soil fertility, and aiding in plant nutrient uptake and retention, biochar improves soil quality. In addition to reducing nutrient loss, it raises the ion exchange capacity and acidity level of the soil. Biochar helps with odor control and

lowering in atmospheric pollutants during landfill operations. It promotes methane oxidation as a landfill capping material, improving environmental health and lowering pollution costs. Increasing the production of biochar from MSW still requires overcoming significant financial and scalability obstacles [78]. These issues call for the development of large-scale production methods that are both economically viable and customized to fulfill particular application requirements. Biochar is a promising material with enormous potential, but more research is needed to maximize its application. Comprehensive utilization necessitates research on its complex properties, including yield, temperature-dependent surface area, and potential contaminants. In the end, biochar made from MSW is a ray of hope for the transformation of waste management techniques. Because of its many uses, it is a promising material for environmental remediation as well as waste reduction, promoting a sustainable and healthy future. To fully realize its potential and turn waste management and environmental sustainability into a ubiquitous and affordable solution, more research and technological advancements are essential [79].

Acknowledgement: *My proud privilege and appreciation for providing laboratory and internet facilities to the Department of Chemistry, Vigyan Mandir, Banasthali Vidyapith, Rajasthan.*

Statements and Declarations

Ethical Approval: *Not applicable.*

Competing interest: *The present study has no technical and financial conflict of interest.*

Author Contributions: *Rajesh Singh Gurjar performed the literature search and data analysis. Ms. Alisha Kakkar oversaw and improvised it and Dr. Sudesh Kumar read the manuscript. All authors read and approved the final version.*

Funding: *No funding is available.*

Availability of data and material: *The manuscript includes data produced or examined throughout this study.*

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