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Review Article

Sustainable biowaste management: Uncovering the environmental footprint of traditional and emerging waste managing technologies

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ABSTRACT

The exponential growth of municipal solid waste (MSW) has intensified the need for sustainable waste management strategies. This review critically evaluates the environmental footprint of traditional and emerging biowaste management technologies, focusing on greenhouse gas (GHG) emissions, their implications for climate change, and their role in resource recovery. Conventional methods such as landfilling, composting, anaerobic digestion (AD), incineration, pyrolysis, and gasification remain dominant yet contribute significantly to environmental pollution. In contrast, emerging technologies like Black Soldier Fly Larvae (BSFL) bioconversion have shown promise in mitigating waste-related emissions while generating valuable by-products. Our systematic analysis synthesizes data from over 400 peer-reviewed studies and evaluates various management strategies based on CO_2, CH_4, N_2O, and NH_3 emissions, energy efficiency, and economic feasibility. The findings highlight BSFL as an effective alternative, reducing CH_4 and N_2O emissions while transforming organic waste into high-value products such as protein-rich biomass, biofertilizers and chitin. However, challenges remain in standardizing operational parameters and optimizing insect breeding conditions to maximize efficiency. This review goes beyond synthesis by providing a comparative environmental assessment of waste management technologies, identifying research gaps, and proposing future directions to enhance sustainable waste valorization practices. We argue that integrating advanced waste treatment technologies with circular economy principles is essential for achieving a sustainable and low-emission waste management system.

1. Introduction

Municipal solid waste (MSW) production has reached unprecedented levels, with an estimated 2.01 billion tons generated globally each year. East Asia and the Pacific account for 23 % of this total, followed by Central Asia and Europe (20 %), and South Asia (17 %). Alarmingly, approximately 30 % of MSW remains uncollected, posing severe challenges to waste management systems and environmental sustainability

Abbreviations: AD, Anaerobic digestion; BSF, Black solider fly; BSFL, Black solider fly larva; CFCs, Chlorofluorocarbons; COAG, Council of Australian Governments; ELV, End-of-Life Vehicles; GHG(s), Greenhouse gas(es); GWF, Global warming factor; GWP, Global warming Potential; HFCs, Hydrofluorocarbons; HTC, Hydrothermal carbonization; MSW, Municipal solid waste; NCBI, National Center for Biotechnology Information; NF_3, Nitrogen trifluoride; PAHs, Polycyclic aromatic hydrocarbons; PFCs, Perfluorocarbons; RCRA, Resource Conservation and Recovery Act; RoHS, Restriction of Hazardous Substances; SF6, Sulfur hexafluoride; VOCs, Volatile organic compounds.

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[1], leading to a significant challenges in waste management and environmental sustainability. This surge in MSW is driven by rapid urbanization, industrialization, population growth and economic development, with the average individual generating 0.74 kg of waste daily [2].

Effective waste management is essential to achieving global sustainability targets. The Sustainable Development Goals (SDGs) emphazise responsible resource use and environmental protection [3,4], with waste management playing a crucial role in SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), and SDG 13 (climate action). However, current waste treatment practices remain largely unsustainable [5]. At present, 70 % of collected MSW is sent to landfills, while only 19 % is recycled, and 11 % is utilized for energy recovery [6]. This reliance on landfilling exacerbates environmental issues, particulary in the management of biowaste, which constitute nearly half of MSW and undergoes decomposition processes that lead to the release of greenhouse gases (GHGs) and other pollutants, including CH_4, CO_2 and NH_3. These emissions contribute to atmospheric pollution, groundwater contamination and public health risks [7]. Improper biowaste disposal is also a major driver of climate change, with the MSW sector ranking as the fourth-largest global contributor to GHG emissions [8,9].

Methane, a predominant gas emitted during biowaste decomposition, holds a global warming potential (GWP) approximately 28 times higher than CO_2 over a century, making its mitigation a priority [10]. Despite global initiatives to reduce emissions, landfills and unauthorized waste dumps in many developing and underdeveloped regions continue to release substantial amounts of CH_4 and other pollutants. This highlights the urgent need for sustainable waste management strategies. The scale of organic waste generation, estimated at 231.01 million tons annually contributes to 604.80 million tons of CO_2 equivalent emissions each year when improperly managed [11]. Traditional waste disposal methods such as landfilling, incineration, anaerobic digestion (AD) and composting, although widely used, are often inefficient in mitigating GHG emissions. Meanwhile, innovative approaches like bioconversion using Black Soldier Fly (BSF) larvae offer a promising alternative (Fig. 1). BSF larvae (BSFL) not only reduce biowaste volume but also significantly lower emissions, attracting growing interest from stakeholders and policymakers [12]. While it can fed with waste, BSF reproduce also rapidly under suitable environmental conditions and its byproducts and breeding waste are well valorized in the industry, including feed and chitin production, making it a good model of circular economy and sustainability.

This review critically examines the environmental and economic implications of biowaste management technologies, with a particular focus on GHG emissions and sustainability. The study aims to bridge research gaps and provide a framework for improving waste management practices. Specifically, this review pursues the following objectives:

1) To **evaluate current biowaste management technologies**, including conventional, non-conventional and biotic methods in terms of GHG emissions, environmental impact and treatment costs.
2) To **identify the most promising technologies** with lower GHG emissions and reduced ecological footprints.
3) To **develop a comprehensive guide** to inform policymakers, researchers and waste management professionals on sustainable practices that address environmental safety concerns and mitigate climate change.

The findings of this study can offer an integrated assessment of GHG emissions in the MSW sector, it provides critical insights for the development of sustainable waste management solutions, aligning with global climate action goals and supporting the transition toward a circular bioeconomy.

2. Methods

This study employs a systematic review methodology to critically evaluate municipal solid waste (MSW) management technologies over the past two decades (January 2002–November 2024). It was carried out using a combination of keywords in various variants in English, such as MSW + incineration/landfilling/composting/AD/BSFL/modern thermochemical process (gasification, plasma gasification, HTC, liquefactions, torrefaction) + gaseous emissions like (CO_2/CH_4/N_2O/SO_2/NH_3)/ trace gases.

Initially, the abstract of the articles have been studied to decide whether they fulfil the criteria; (i) identify gaps in applied waste management technologies and demonstrate the existing contribution to GHG emissions; (ii) consider only scientific papers published in the most reputable academic research databases, for example, Google Scholar, Science Direct, and NCBI (Fig. 2). Cross references, discovered through a comprehensive search, were taken into account; (iii) examine only studies that evaluated the emissions of at least one greenhouse gas and provided an exhaustive description of the gas measurement (however, each study contains different assumptions corresponding to waste composition, the energy network and the gas management model, which makes it difficult to determine). The papers selected for this review were not limited to any particular geographic location and language. The overall comparison of each technology is based on its benefits and

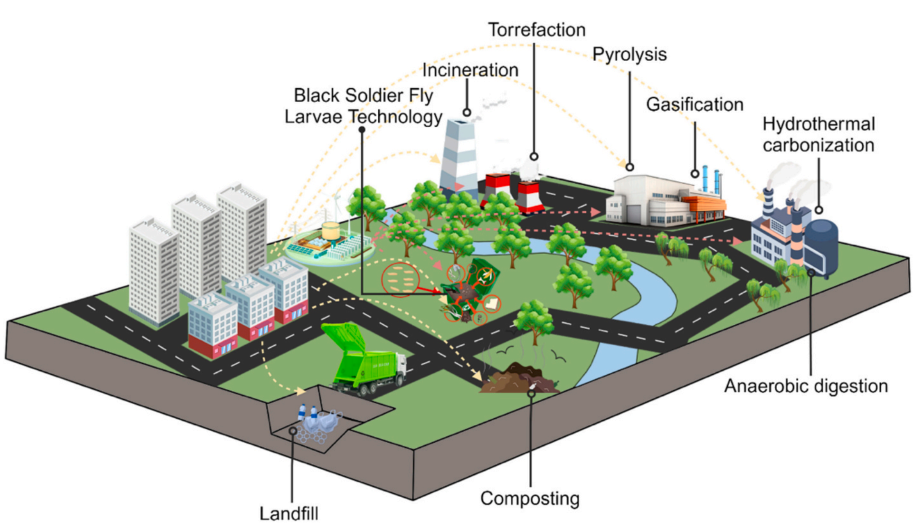

Fig. 1. Waste management technologies.

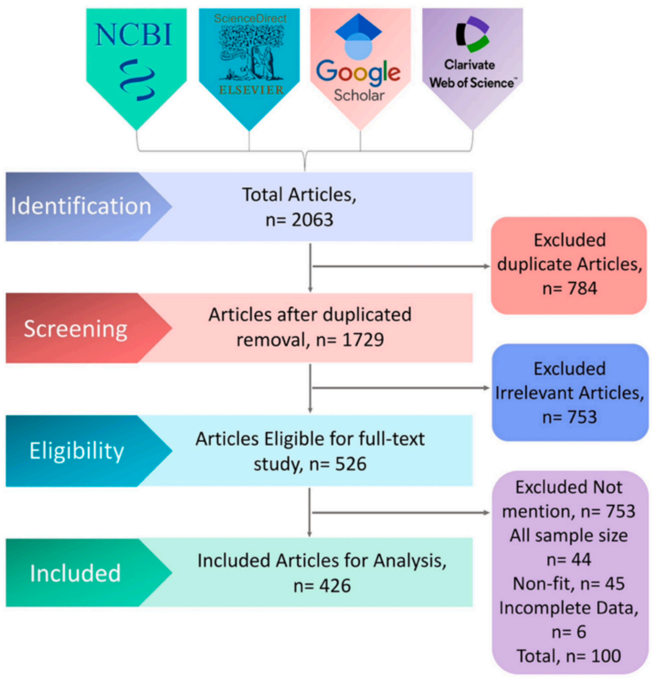

Fig. 2. Systematic representation of the collected data.

implications.

The selection of studies was based on specific criteria to ensure the relevance and reliability of the reviewed literature. Empirical studies analyzing municipal solid waste (MSW) treatment methods with explicit quantification of greenhouse gas (GHG) emissions were prioritized. Additionally, studies providing methodological details on waste composition, energy network assumptions and gas measurement techniques were included to enhance the technical rigor of the analysis. Articles discussing economic and environmental trade-offs, particularly those addressing treatment costs and energy recovery, were also considered essential. The parameters and additional factors including time, resources, and influencing factors were also considered to maximize the true evaluation. Six parameters have been evaluated against each technology and presented in tables and figures separately to add worth.

The paper is structured into two sections. In the first section, the findings of the literature review of exciting technologies are presented, while in the second section, a comparison of BSFL technology with other management strategies based on the previously mentioned parameters.

3. Results

3.1. Literature analysis

Our keyword search of the literature resulted in 2063 scientific studies regarding the merits and demerits of applied waste management technologies over the past two decades (Fig. 3). Based on the findings of the search, 784 literature sources were rejected as duplicate works; 753 scientific studies were denied due to the lack of information on GHG (or one of them) that are produced using the described technology, including 117 works rejected due to inaccurate definition of units for specific technologies parameters. Finally, 426 papers were selected and analyzed to reveal the necessary information for the current study. Among the most frequently investigated technologies were the following (given in decreasing order of frequency of mention in the scientific literature): Landfill, Incineration, AD, Composting, Pyrolysis, Gasification, Hydrothermal Carbonization (HTC), Liquification, Torrefaction and BSFL (Fig. 3).

The following were the most frequently used factors for suggesting a given technology (in decreasing order of frequency of use for recommending a specific technology): Availability and ease of implementation with no special equipment or other capital investments are required, minimal impact on soil, natural water or air through heavy metals and toxic substances, cost per ton of waste and formation of GHGs.

3.2. GHG emissions from anaerobic digestion

Anaerobic digestion (AD) is a key process in waste management, where organic matter is decomposed by micro-organisms in an oxygen-deficient environment. This process results in the production of biogas, mainly composed of CH_4 and CO_2, along with digestate, a nutrient-rich byproduct often used as a fertilizer. Biogas typically contains 40–70 % CH_4 and 30–35 % CO_2, making it a valuable resource for various

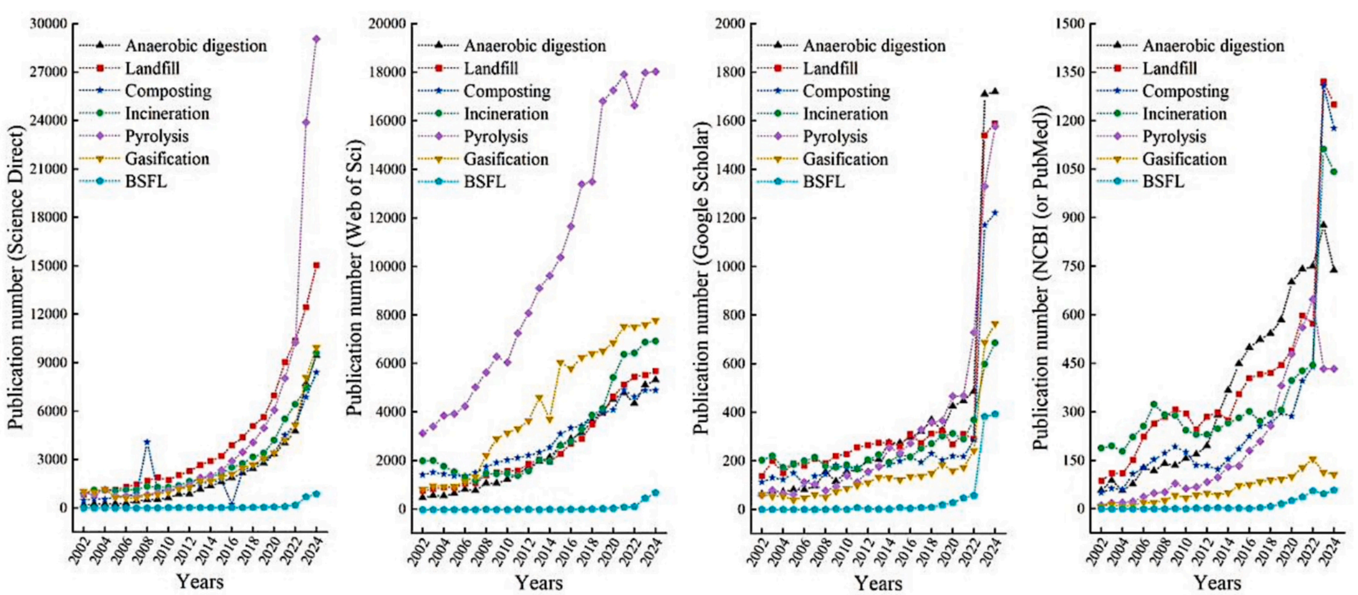

Fig. 3. Number of academic publications about each technology and trend (Sources) Science Direct, Web of Science, Google Scholar, and NCBI or PubMed from January 2002 to November 2024.

applications, such as direct power generation, transportation fuel, injection into national gas grids, or as part of combined heat and power systems (CHP) or fuel cell [8]. Among these applications, using biogas as a vehicle fuel is considered the most economically viable and environmentally sustainable option [13]. However, the high concentration of CO_2 in biogas poses certain challenges, including reduced heating value, lower combustion efficiency, diminished economic returns and potential corrosion of system components [14]. To address these issues, numerous post-treatment techniques have been developed to purify biogas by removing impurities such as CO_2, water vapor, H_2S, etc. [15].

Regarding the CH_4 content in biogas, approximately 70 % of the CH_4 production originates from the decomposition of acetic acid, while the remaining 30 % is derived from the redox reaction between carbon dioxide (CO_2) and hydrogen [16]. In terms of GHG emissions, the cumulative global warming factor (GWF) for AD and digestate utilization was calculated, offering a comprehensive assessment of the process's environmental impact [17]. It generated from AD processes around 90–200 kg CO_2 per ton of waste, 2–40 × 10^{-6} kg CH_4 per ton of waste, 0.05–2 × 10^{-6} kg N_2O per ton of waste [18] and 0.3–3 × 10^{-3} kg NH_3 per ton of organic waste [19]. The human carcinogenic potential (HCP) associated with AD systems was found to be 3.98 × 10^{-4} kg 1,4-dichlorobenzene ($C_6H_4Cl_2$) per ton of the organic fraction of MSW [20]. The percentage of biogas enhancement achieved through AD between 4 % to 39.28 %. While thermal hydrolysis presents a similar enhancement potential (up to 31.48 %), some studies have reported negative effects from its implementation [21].

3.3. GHG emissions from landfill

Landfill gas (composed of around 41–48 % CH_4 and 32–40 % CO_2 by volume) is produced continuously through various long-term biochemical reactions occurring in a landfill with household garbage. Landfills release these GHG into the atmosphere. They produce 500–700 kg CO_2 ton^{-1} of waste, 100–1000 × 10^{-6} kg CH_4 ton^{-1} of waste, and 5–20 × 10^{-6} kg N_2O ton^{-1} of waste [22], and 5–10 × 10^{-3} kg NH_3 ton^{-1} of organic fraction of MSW [23].

According to Kaushal and Sharma [24], annual GHG emission from a landfill is critical, reaching up to 62.86 G tons. As stated by various studies, landfills and old waste deposit sites on a global scale emit approximately 40–60 M tons of CH_4, contributing to around 11–12 % of the global anthropogenic CH_4 emissions, which add up to 500 M tons per year. This places landfills in the third position following rice paddies (60 × 10^6 tons $year^{-1}$) and ruminant livestock (85 × 10^6 tons $year^{-1}$) [25]. Still, generated CH_4 can serve as an energy source if recovered from the landfill, and the resulting manure can enhance agricultural productivity [26]. Under a sanitary landfill, 1.16 kg of C emissions can be generated from 1 kg of MSW. In comparison, the carbon emissions are reduced to 0.79 kg under a regular landfill. When MSW is composted, the emissions decrease further to 0.30 kg, while burning MSW results in 0.51 kg of carbon emission [27]. In other words, more than three times higher carbon emission occurs from sanitary landfills compared to compositing, almost two times higher compared to regular landfills, and two times higher than burning [28]. Regarding carbon dioxide emissions, landfill waste management accounted for the higher production (568.98 kg CO_2-equivalent ton^{-1} of MSW). It is estimated that by 2030, the net emissions of waste management will amount to 33 kg CO_2-equivalent $year^{-1}$ [29].

Another serious concern about landfills is the possible release of contaminants and microorganisms into groundwater resources due to waste management activities [30]. Contamination of air and water is caused by landfill emissions of carbon monoxide, nitrogen oxides, sufur oxides, and heavy metals [31]. Moreover, landfills produce a wide variety of primary and secondary pollutants into the environment, including dust, metals, acid gases, oxides of nitrogen, Sulfur and microplastics. Landfills may also liquefy during earthquakes if they are not stabilized. Leachate poisoning of groundwater is typically considered the worst environmental hazard landfills produce (explosion threats, vegetation destruction, dust and air emissions, etc. [32]. Several studies indicate that if no barriers prevent leachate from entering the groundwater from landfills, groundwater may be contaminated for a lengthy period after waste disposal has ceased [33].

3.4. GHG emissions from composting

About 90 % of the GHG emitted by composting are carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), hydrogen sulfide (H_2S) and volatile organic compounds (VOCs) [34]. The quantity and the composition of these gases can vary as the amount of waste in composting is greatly affected by the type and composition of waste. Barrington et al. found that 14–51 % of the organic carbonin the raw material can be emitted into the atmosphere as CH_4 and CO_2 during the composting process [35]. A similar trend was noted for nitrogen compounds, as Ren et al. found an initial loss (about 16–74 %) of nitrogen content in the form of NH_3 and N_2O emissions during composting [36].

The composting process produces 200–500 kg CO_2 ton^{-1}, 0.01–1 × 10^{-3} kg NH_3 ton^{-1} of MSW [37], more than 0.01–0.1 × 10^{-6} kg CH_4 ton^{-1} and more than 0.01–0.1 × 10^{-6} kg N_2O ton^{-1} of MSW [38]. The highest CH_4 emissions occur during the mesophilic phase when the conditions are anaerobic (65–95 %) [39], as also confirmed by Nguyen et al. [40]. The emission rates can also be influenced by season, as they were 0.64 × 10^{-3} kg CH_4 ton^{-1} of dry waste $hr.^{-1}$ in winter, 5.04 × 10^{-3} kg CH_4 ton^{-1} of dry waste hr. – ^{1} in spring, and 4.01 × 10^{-3} kg CH_4 ton^{-1} of dry waste $hr.^{-1}$ in summer. It should be mentioned that the significant CH_4 contribution to CO_2-equivalent emissions underlines the importance of composting as a CH_4 source for energy production [41]. Regarding N_2O, the emission of increases during the denitrification process as the pH value decreases to 5.5 from 7 [42]. Vermicomposting exhibited lower levels of N_2O emissions (5.76 kg CO_2-equivalent ton^{-1} dry waste) compared to thermophilic composting, which exhibited higher emissions (12.29 kg CO_2 -equivalent ton^{-1} dry waste) [36].

Composting involves some critical points. As for landfilling, many harmful substances generated during the composting process can lead to secondary pollution. Besides the lack of improved technology, the extended period and large area requirements required for composting make it challenging to commercialize compost [43]. Several studies have explored methods to mitigate GHG emissions from composting. Physical approaches focus on reducing emissions by adsorbing GHG within material pores. Mao et al. demonstrated that the addition of zeolite resulted in a 69 % and 67 % reduction in the CH_4 and N_2O emissions, respectively, during the composting of pig manure [44]. Biological additives can also influence GHG emissions by modifying the microbial community composition. For example, Fukumoto et al. illustrated that N_2O emissions could be decreased by incorporating nitrite-oxidizing bacteria during composting [45].

3.5. GHG emissions from incineration

Incineration is commonly employed to destroy mixed MSW, as it notably reduces the waste mass and, with special equipment, may provide the recovery of the produced thermal energy. As a result, MSW incineration has attracted attention in countries with a shortage of landfill sites and a lack of modern environmentally friendly technologies. A high reduction degree is achieved by incinerating, which does not require further decomposition. Additionally, the ashes may be utilized as a soil cover. The pathogens in the MSW are eliminated and the perishable organic matter that produces harmful gases is oxidized safely. The burning operation is reliable, clean and stable [6]. Particulate matter, metals and acid gases, namely H_2S, CO_2 and oxides of nitrogen and sulfur (NO_x and SO_x) are the most prevalent air contaminants from the incineration process [46].

MSW incinerators emit CO_2 and N_2O as part of their GHG emissions from the combustion of fossil carbon and nitrogenous materials. Incineration acts as a carbon sink, reducing net carbon emissions to 28.56 kg CO_2-equivalent ton^{-1} of MSW, from 347 to 371 kg CO_2-equivalent ton^{-1} of MSW (from incineration) and 735–803 kg CO_2-equivalent ton^{-1} of MSW (from co-combustion) which is 40 % reduction in direct emissions. A limited quantity of CO (GWP 1.9 kg CO_2-equivalent (kg CO^{-1}) may also be released from combustion facilities [47]. An incinerator emitting 10^{-2} kg N_2O ton^{-1} of MSW (GWP of 298 × 10^{-3} kg CO_2-equivalent (10^{-3} kg $N_2O)^{-1}$ emitted) translates to 2.98 kg CO_2-equivalent ton^{-1} of MSW incinerated [48]. According to other sources, incinerators produce 700–1200 kg CO_2 ton^{-1} of MSW [49], 0.1–1 × 10^{-6} kg CH_4 ton^{-1} of waste [50] and < 1 × 10^{-6} kg N_2O ton^{-1} of waste and 0.1–1 × 10^{-3} kg NH_3 ton^{-1} of waste [51].

The other side of the coin is that incineration causes water pollution, stench, noise and vibrations that affect residential and business neighbors. Fly ash and bottom ash are harmful and must be handled carefully. Besides GHG emission, during incineration by-products such as particulate matter, metals, acid gases, nitrogen oxides and sulfur contribute to secondary pollution, as do furan, dioxin and mercury. Moreover, compared to coal power plants, waste incineration creates 2.5 more CO_2 while providing the same amount of electricity, being heavily harmful for the environment [52].

3.6. GHG emissions from pyrolysis

Pyrolysis is a thermochemical decomposition that involves high-temperature combustion in the absence of oxidizing agents. It is another viable strategy to generate renewable energy while offsetting the emission of GHGs. The products obtained from waste pyrolysis include solid forms like charcoal and biochar, as well as liquid and non-condensable gases such as light alcohols, ketones, aldehydes, organic acids, CO, CO_2, CH_4, H_2 and N_2. The composition of the solid residue varies depending on the pyrolysis process parameters [53]. The condensation/liquefaction of gases created during pyrolysis forms bio-oil. At 850 °C under 100 % N_2, pyrolysis gas yields 20 % CO_2 and 40 % CO [54]. The pyrolysis and the combustion units for bio-oil are the primary sources (> 30 %) of GHG emissions [55].

Biochar is the solid, porous product of the pyrolysis process and can alter esteemed CO_2 production as it can adsorb molecules on its surface, thereby seemingly reducing CO_2 emissions. The construction-related GHG emissions from biomass thermal conversion systems include 5.82 × 10^5 kg CO_2-equivalent from biomass pyrolysis. Biomass pre-treatment, like drying, crushing, etc., accounts for 34 % of the overall global warming potential (GWP) in pyrolysis. The biomass collection and transportation in polyol production through pyrolysis adds 3.6 % to the total GWP [56]. Moreover, the calculated emission factor for every ton of MSW processed using pyrolysis is −503 kg CO_2-equivalent ton^{-1} of fresh waste indicating a negative value.

For every ton of fresh MSW, carbon loss from organic sources is about 506 kg CO_2-equivalent ton^{-1}. GHG emission intensity during pyrolysis of MSW is estimated as 1.55 × 10^{-2} kg GHGs per 1 MJ of generated energy. The largest proportion of the total GHG emissions (89.23 %) from pyrolysis plants comes from the operation parameters and maintenance process [57].

Waste pyrolysis produces 400–900 kg CO_2 ton^{-1} of MSW [58], 0.4–4 × 10^{-6} kg CH_4 ton^{-1} of MSW [59], <1 × 10^{-6} kg N_2O ton^{-1} of waste [60], and 0.01–0.2 × 10^{-3} kg NH_3 ton^{-1} of waste emissions [61]. An initial investment of $0.2 million is required for the pyrolysis plant when the raw material flow rate is 14 kt per year, producing ten kilotons of fuel per year. Pyrolysis requires an electrical input of 20-kW h to treat one ton of trash.

The gases produced from pyrolysis, such as carbon monoxide (CO), hydrogen (H_2) and carbon dioxide (CO_2), can be utilized as energy carriers. However, lack of availability and consistency in feedstock quality, inefficient and costly sorting, lack of markets owing to lack of standardized products, and lack of clarity in plastic waste management rules are the primary challenges to the widespread use of pyrolysis to recycle plastic waste. At the same time, by-products generated during pyrolysis, including H_2, CH_4, CO and CO_2, can contribute to secondary pollution.

3.7. GHG emissions from gasification

Gasification is an established method that utilizes oxygen, steam, and heat in a controlled process to convert biomass into hydrogen and other products without the need for combustion. It is a partial oxidation process which converts biomass into gaseous fuel (synthesis gas) at high temperatures [62]. Since biomass growth removes carbon dioxide from the atmosphere, this method has a potential for low net carbon emissions, especially if combined with long-term capture, utilization, and carbon storage. Syngas, heat, electricity, bio-fuels, fertilizer, tar (liquid residue) and biochar (solid residue) are the essential end products of waste gasification. The composition of gases synthesized during the process, which are constituted by CH_4, H_2, CO, and CO_2, depends on processing parameters like gasifying agent, temperature, and use of catalysts [63]. The amount of CO_2 emitted during gasification depends on the gasification conditions and feedstock used and typically ranges from 100 to 500 kg CO_2 ton^{-1} of waste; additional products of the process are 0.1–5 × 10^{-6} kg CH_4 ton^{-1}, 0.1–1 × 10^{-6} kg N_2O ton^{-1} and 0.5–2.5 × 10^{-3} kg NH_3 ton^{-1} of waste [64].

The existing biomass gasification technology still faces challenges, for instance, elevated costs from the application level. Furthermore, from the perspective of the entire life cycle of biomass power generation, the complete chain process starting from biomass collection can result in critical GHG emissions [65]. Wang and Yang studied the biomass gasification power technology and found that the overall life cycle GHG emissions for this technology is 8.68 × 10^3 kg CO_2 eq, with the total cost amounting to 674 USD/10^4 kWh [66]. Within the biomass gasification phase, using natural gas as a heat source for the biomass pyrolysis and gasification reaction leads to 15 % of the emissions. In comparison, the gas turbine power generation process accounts for 71 %. The whole lifecycle carbon emission of biomass gasification power technology is 0.868 kg CO_2eq per kWh generated. Similar to other fossil fuel combustion processes, gasification results in the release of greenhouse gases (GHGs) and toxic by-products, including heavy metals and dioxins, into the atmosphere. The process generates various emissions such as carbon dioxide (CO_2), hydrogen (H_2), carbon monoxide (CO), tar vapors, water vapor, and ash particles, all of which can contribute to secondary environmental pollution. Key environmental concerns associated with gasification include air and water contamination, emissions from mass-burn incinerators, challenges related to ash disposal, and the formation of hazardous by-products.

3.8. GHG emissions from hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical conversion process that utilizes heat to transform the wet biomass feedstock to hydro-char (a coal-like product). The process is performed in a reactor under autogenous (automatically generated) pressure at from 180 to 250 °C. The residence time of feedstock is between 0.5 and 8 h [67]. HTC advantages include the treatment of wet waste, allowing feedstock conversion without needing pre-drying, while other thermochemical conversion methods, such as pyrolysis require further pre-treatments. Water is used as a solvent medium to produce hydro-char, which is the end product of the reaction [68]. The carbon efficiency of the HTC (the quantitative comparison of carbon content in the final product to initial feedstock) is higher than other biomass conversion techniques. Hydro-char serves as a “carbon sink” storing the total carbon content of the raw material. It's utility as a direct source of energy without requiring further treatments is beneficial in reducing GHG emissions [69]. The HTC only needs 20 % of the electrical power and around 70 % of the thermal energy. The price of waste treatment by HTC is $117 per ton, being more than 5-times lower than pyrolysis cost [70]. The gaseous effluents comprise CO_2 (90 %) and a mixture of hydrocarbon gases (H_2 and CO). The by-products generated from HCT are hydro-char, liquid (rich in nutrients), and gas (mainly CO_2) phases.

The total heat required for operating an HTC reactor is 22.1×10^5 MBTU per year (2.3×10^6 MJ $year^{-1}$) [71]. Hydrothermal carbonation contributes to greenhouse gas emissions, ranging from 30 to 140 kg CO_2 ton^{-1} and 0.5 to 3.5×10^{-3} kg NH_3 ton^{-1} of HTC products [72]. CH_4 emissions are normally minimal during HTC, with typical values between 0.1 and 3×10^{-6} kg CH_4 ton^{-1} and 0.1 to 1.5×10^{-6} kg N_2O ton^{-1} of HTC product. Depending on the substrate and ambient conditions, waste processing may take 5.0–8 days for HTC. The pH required for HTC is 2–12. Using HTC is also a viable strategy to reduce waste volume, as it can decrease up to 90 % [73].

3.9. GHG emissions from torrefaction

Torrefaction is a thermochemical process that strives to reduce the moisture and volatiles contents from the biomass, thereby enhancing its fuel characteristics such as improved grind ability, more homogeneous composition, reduced biological activity, hydrophobic behavior and higher energy density. Torrefaction involves the conversion of biomass feedstock into medium-grade solid biofuels (bio-coal) through thermal conversion (or pretreatment). Bio-coal includes biochar and hydrocar that, are stable, homogeneous, and possess greater energy densities and calorific values than the initial biomass feedstock [53]. During torrefaction, effective inorganic matter content, mainly Ca, Si and K are released into the environment. The torrefied biomass loses only around 10–20 % of its volume compared to the dry feedstock [74]. All the gas streams produced during the process are directed toward the combustor and are considered to be burned completely to produce CO_2 [75].

The resulting emissions arising from biomass storage, such as CO_2, CH_4 and N_2O, can contribute to GHG emissions. These gaseous emissions during storage are associated with the loss of dry matter. The degradation extent depends on the feedstock nature, storage environment and moisture content [76]. The amount of CO_2 emitted during torrefaction can range from 30 to 90 kg CO_2 ton^{-1}, 0.1 to 5×10^{-6} kg CH_4 ton^{-1}, 1 to 10×10^{-6} kg N_2O ton^{-1} and 1 to 10×10^{-3} kg NH_3 ton^{-1} of torrefied biomass [77]. Regarding duration, the torrefaction process takes 60 min, depending on ambient conditions and the type of substrate. The waste's pH ranges from 5 to 8 for torrefaction, while the cost of treatment for one ton of trash by torrefaction is $164 [78]. Corrosion deposits on boiler tubes are not mitigated by torrefaction (all ash components of biomass are still present in TB). Inadequate data exist on the process's efficiency, the qualities of the end product, and the volatiles' composition [79].

3.10. GHG emission from black soldier Fly larvae technology

Considering traditional waste management methods' drawbacks, new technology to digest wastes with insects has emerged in recent years, which can be used as a protein source while reducing land and energy requirements and mitigating global warming. *Hermetia Illucens* is recognized as one of the promising species to shield the current challenge as several practical approaches have been developed for ensuring nutrient retention and minimizing nitrogen and carbon losses in composting of BSFL [73]. BSFL is a new approach with a wide application in treating biowastes. Therefore, it has attracted considerable research interest globally [80,81]. In previous research studies, organic wastes were predominantly bio-treated, and residues were utilized as fertilizers. Moreover, larvae provide a rich source of protein and fats, which are useful for producing biodiesel and animal feed [82]. The application of various substrates can increase the C/N ratio, thus chemical agents or mineral additives can be added to change substrate aeration rates.

A BSFL treatment can decrease gaseous emissions, namely CH_4, N_2O, and NH_3 emissions, and reduce global warming potentials (GWP), in an environment-friendly manner. Indeed, BSFL can reduce CH_4 and N_2O emissions compared to composting. This implication is extremely important because as it is assumed that CH_4 contributes 28–34 times as much to global warming as CO_2. After all, BSFL deoxidizes acetic acid and CO_2/H_2 via methanogenesis [23]. The emission of N_2O, another potent GHG primarily produced during nitrification and denitrification processes as an intermediate or a byproduct, greatly influences global [83]. Nitrification involves the conversion of ammonium salts to nitrates by microorganisms in the presence of oxygen while during denitrification, NO_3 is converted in N_2; minimal N_2O emissions characterize BSFL production, and in various instances, there is no significant difference of its concentration from the ambient air. This is attributed to the aeration caused by BSFL feeding and movement, which inhibits denitrification by decreasing the number of denitrifies [84]. Because CO_2 is a biogenic gas, it is usually not taken into consideration when assessing global warming potential. Quantifying CO_2 emissions is still important for comprehensively understanding carbon cycling in BSFL bio-treatment. During the treatment process, the primary gaseous product is CO_2, which can indicate the metabolic activities of BSFL and microorganisms [85]. The BDFL gas emissions are represented in Fig. 4. According to the results of available studies, BSFL produces 2–40 kg CO_2 ton^{-1} of waste, $<1 \times 10^{-6}$ kg CH_4 ton^{-1} of waste, $<1 \times 10^{-6}$ kg N_2O ton^{-1} of waste [86], and 3–4 $\times 10^{-3}$ kg NH_3 ton^{-1} of waste emissions [87].

In all the treatments, the CO_2 emission rate first increased, then decreased, and then eventually became relatively stable; Since the CO_2 emitted during BSFL biowaste treatment is biogenic, it is not expected to have a considerable impact on the greenhouse effect [88]. Hence, only CH_4 and N_2O were considered. The GWP of CH_4 was taken to be 25- and that of N_2O to be 298-fold, compared with that of CO_2 (GWP = 1). During the process, the total GHG emissions varied from 0.09 to 0.50 kg CO_2-eq per ton of dry waste (Fig. 5). Composting aerobically produces lower levels, to dispose of waste O_2 from food waste degradation, BSFL bio-waste treatment should be strongly suggested. Therefore, for every kilogram of food waste treated the total GHG emissions were 96 g CO_2. In contrast, the emissions of major GHGs (CH_4 and N_2O) were equivalent to 0.38 kg CO_2-eq per ton of waste treated [89]. Few studies focus on the sustainability of BSFL treatment of wastes. Mertenat et al. and Ermolaev et al. found that assessing the environmental sustainability of the waste treatment method using BSFL requires investigation of direct GHG emissions and carbon and nitrogen recycling during treatment, for which further exploration based on multiple raw material and process parameters is needed.

Comprehensive Table 1 contains the selected criteria for deciding on the effectiveness and practicality of applying the technology under specific conditions. Indeed, in addition to the GHG emissions and pollutants produced from each process (Table 2), shareholders, entrepreneurs, politicians, and decision-makers must consider the cost of processing per ton of waste, processing time, etc.

4. Discussion

Detailed information on emissions from the most common technologies demonstrates that the environmental issue is not completely solved. This means that by trying to resolve the waste accumulation challenge, the world faces another problem - global warming due to greenhouse gas GHG emissions. Numerous studies confirm this complication. Consequently, in the last two decades, the research literature on waste management technologies like landfills, pyrolysis, and anaerobic digestion (AD) has been actively growing. At the same time, authors emphasize the negative sides of these technologies as illustrated in Fig. 6 and Fig. 7, particularly AD and landfills, which have the highest GHG emissions. Consequently, achieving a positive impact in ensuring ecological safety is impossible. Regarding pyrolysis, the significant CO_2 emission and the high cost of waste processing are clearly evident from the literature (Table 1).

There has been a gradual and moderate increase in research on

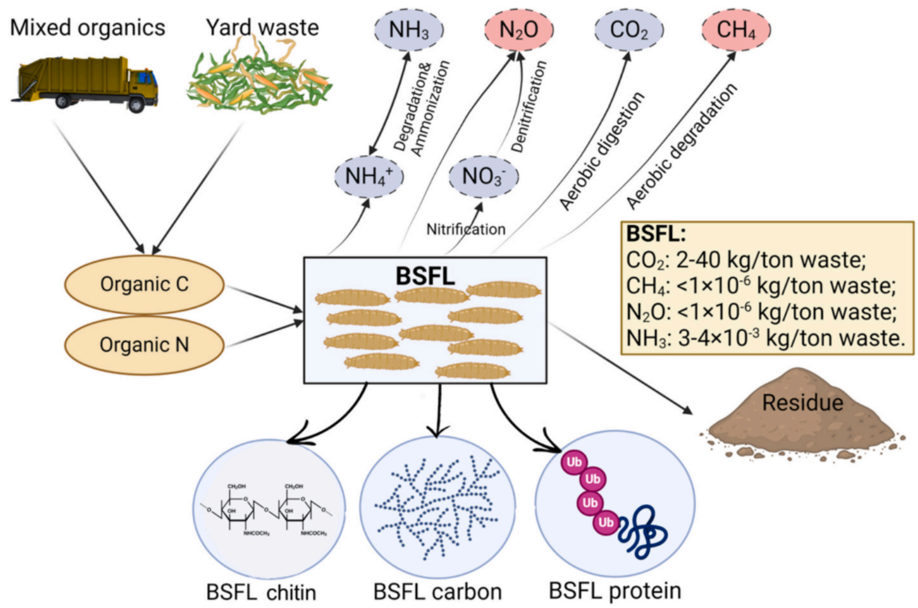

Fig. 4. Gases emission from BSFL carbon and nitrogen metabolism.

gasification, composting and incineration technologies. These technologies differ in producing mainly NO_2 and NH_3 (gasification) and CO_2 (composting and incineration). Limited studies have been published for HTC, torrefaction, and BSFL technologies. Moreover, significant publications started to appear only in the last 12 years. No such studies were found until 2009. Among them, the number of BSFL studies has show moderate growth. Compared to HTC ($117/ton) and torrefaction ($164/ton), BSFL technology has the lowest waste processing cost of $6–16/ton **(**Table 1**)**. At the same time, the BSFL technology is contra-distinguished by the absence of the formation of CH_4 and N_2O and the low production of CO_2 and moderate NH_3 emissions. Such advantages make it possible to list BSFL among those innovative technologies that deserve further investigation and practical development.

4.1. Impact of waste management on climate change

As a result of our energy production, product consumption, and irresponsible waste management; carbon-based particles from the burning petroleum products are released into the atmosphere and directly contribute to climate change. Consequently, the air temperature increases, resulting in the devastating greenhouse effect [134]. Multiple GHGs are released into the atmosphere during waste disposal and treatment, contributing to global warming. It has been determined that direct and indirect emissions from waste treatment, recovery, and disposal activities substantially contribute to climate change [135]. Specific contaminants are produced even when garbage is recycled (even though the reduction in fossil fuel consumption due to the utilization of recycled materials offsets the environmental impacts associated with obtaining new raw materials). Transforming recycled materials into a marketable end product and replacing recycled items with raw materials severely impact the environment. Given the above, it can be argued that improperly handling of MSW contributes to serious negative environmental consequences.

The GHG such as CH_4, N_2O, and CO_2, are generated in considerable quantities by anaerobic digesters. During the production and utilization of biogas, both combustion processes and diffuse emissions contribute to releasing dangerous compounds and air pollutants. Regarding CO_2, biogas combustion results in the effective oxidation of CH_4 and conversion to CO_2 at 83.6 kg per GJ [136] (taking into account biogas composition containing 65 % and 35 % CH_4 and CO_2, respectively). This pollutant is also emitted during the handling and storage of biomass during the processing of digestate. CO_2 is regarded as biogenic and is ascertained to not affect the climate when produced as a byproduct of biogas combustion or the emission of digestate. The most concerning air pollution associated with direct emission from the biogas combustion are the nitrogen oxides (NOx) levels. Overall, a conversion to bio-methane production can potentially cut GHG emissions and improve air quality. However, questions have been expressed concerning the sustainability of CH_4 losses in the off-gas. Composting is the primary source of CH_4, CO_2, CO, N_2O emissions (60–70 %) and NH_3, H_2S, and VOCs emissions (>90 %) [53]. When compost is applied to edible plants, the risk of contamination becomes a significant concern. Air and water are two of the most significant environmental components that might be damaged by composting waste. Some of these gases, like NH_3, CH_4 and N_2O, have environmental consequences and may be regulated.

The landfill's CH_4 emissions are the waste industry's most significant GHG emissions, producing around 1500 Mt. CO_2-eq. In landfill waste, microbes consume organic carbon, creating decomposition. As bacteria break down organic molecules over time, CH_4 (about 50 %), CO_2 (approximately 50 %), and other gaseous compounds (1 %) are produced [137]. Methane-producing microorganisms thrive in landfills when rubbish is buried, and deposits are covered with impermeable material. Temperature, humidity, and the availability of optimal nutrients (organic waste) result in enhanced biochemical activity and landfill gas generation [138]. As a result of bacterial activity, even after waste disposal ceases, carbon breakdown in landfills continues to produce emissions. As chemical and metabolic processes need time, only a limited proportion of a waste's carbon is released during the first year of treatment [139]. After landfills, incineration, which contributes to around 70 Mt. CO_2-e generated for one year, is anticipated to be the next largest contributor to GHG emissions in the management of solid wastes [140]. CH_4, CO_2, and N_2O emissions are generated by the combustion of the facility's fuel generation, heat and power consumption, and material manufacture. Incinerators discharge more toxins and pollutants, negatively affecting regional air quality [141]. Producing electricity from trash incineration generates much higher GHG emissions than conventional techniques, like natural gas (340 g CO_2eq per kWh). Incineration is thus clearly not an environmentally friendly alternative [142].

Regarding pyrolysis, nine times more GHG emissions are produced by this process than by mechanical recycling. Besides ash, char, and air pollution, these facilities create synthetic gases and oils owing to the absence of oxygen and severe temperatures, thus endangering human

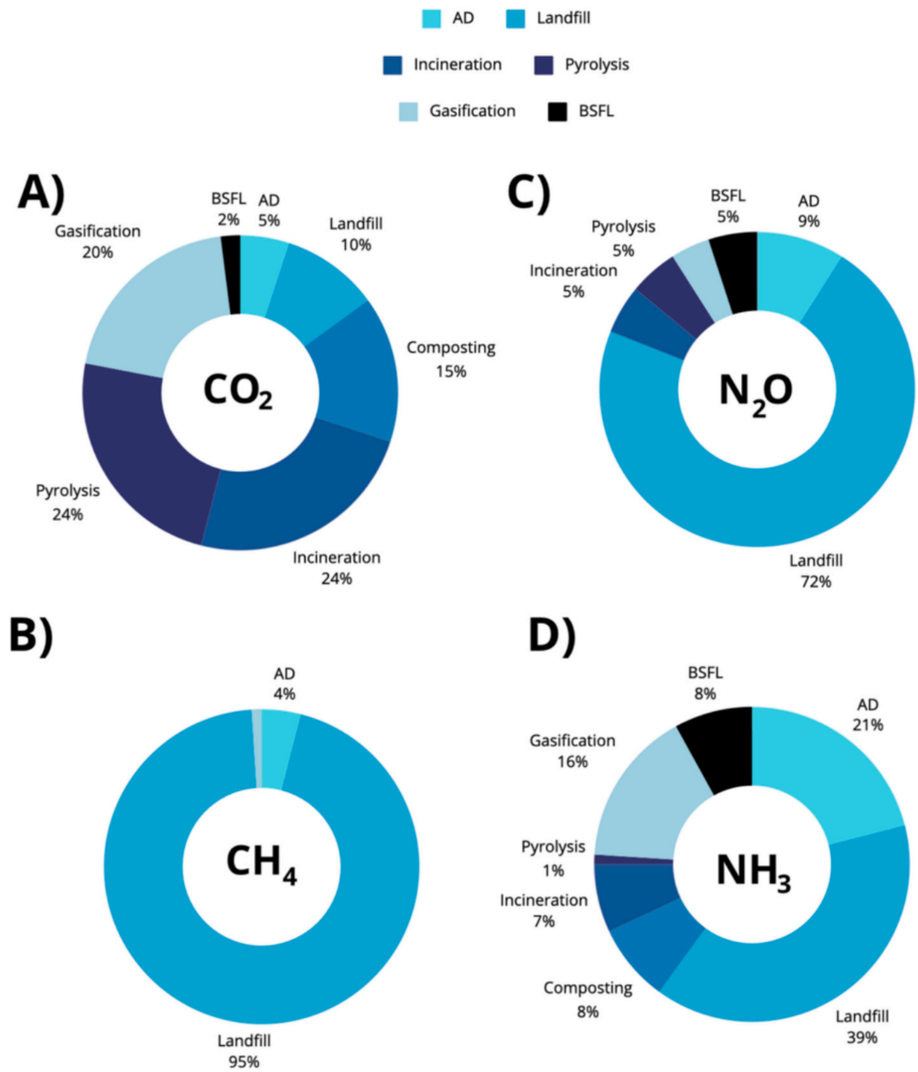

Fig. 5. Composition and emission analysis of GHGs from waste management technologies. Letters on the row indicate A) CO_2 (Total: 20.48 10^2 kg/ton of waste); B) CH_4 (Total: 948.49 10^{-6} kg/ton of waste); C) N_2O (Total: 20.94 10^{-6} kg/ton of waste); D) NH_3 (Total: 12.78 10^{-3} kg/ ton of waste).

health and the environment [143]. The emission of harmful heavy metals into the environment due to pyrolysis leads to accumulation and growth of more hazardous materials [144]. The key to recovering cost-effective and clean energy from the pyrolysis of MSW is to address issues with the emission and generation of these pollutants [106]. In addition to mass-burn, water and air pollution, ash disposal, and other byproducts, gasification operations pose several environmental concerns. Gasification produces CO_2, H_2, hydrocarbon oils, char and ash as byproducts [145]. These plants produce synthetic gases and lipids, consequently generating low-oxygen ash, char at high temperatures, and air pollution. The presence of gasification by-products gravely threatens human and environmental health.

The aims of biofuel research and development include the reduction of human-made CO_2 emissions, improving the greenhouse effect, and mitigating of global [138]. The most efficient processes available to convert biomass into biofuels are thermochemical conversion processes, with torrefaction having the lowest global warming potential. Higher torrefaction temperatures result in the volatilization of phenol, acetone, and other pollutants, increasing the cleaning of flue gas difficulty [146].

4.2. Global policy and governance framework for sustainable waste management

Several policies are being implemented by developed and developing countries to mitigate the harmful impacts of industrialization and urbanization resulting in large amounts of waste. Still, these actions fall short of establishing effective procedures that adequately address the demands of society, especially when it comes to managing MSW, where numerous stakeholders must cooperate and a comprehensive plan of action is needed regarding targets and policies for sustainable cities [147]. This section of the article offers a short overview of the adopted policies and governance framework by various nations, such as the United States has shifted its focus to the prevention of pollution and conservation of resources as a result of the Resource Conservation and Recovery Act (RCRA; substantially amended in 1984), the Pollution Prevention Act (amended in 2002), and the Resource Conservation Challenge (2004) [148]. Although the RCRA lays out the basis for handling solid and hazardous waste, MSW is governed by local ordinances. Emission reduction of GHG, management of hazardous chemicals, and conservation of natural resources are all part of the United States' current waste management strategy [149]. The Strategic Plan for 2010–2014 was developed following the Pollution Prevention Act [150]. Netherlands and Norway embraced an early, all-encompassing

Table 1
Cost per ton, substrate reduction and process parameters.

Technology	Substrate	Volume Reduction	Moisture Content	Process Parameters	Time	Cost/ton	pH	Energy Input	Energy Output	Process end-products
Anaerobic Digestion [90,91]	Food waste, Biosolids, Manure, agriculture waste and other Biodegradable organic waste,	30–70 %	60–80 %	Temperature, pH, Hydraulic retention time, Organic Loading Rate, and sludge retention time	Mesophilic (15–30 days) Thermophilic (12–14 days)	$30–50	6.8–7.2	Sunlight and heating are required to maintain the temperature in winter	Produce 300 kWh of energy per ton of waste	Biogas, Bio fertilizer, Energy-rich organic Compound, Landfill gases, CH_4, CO_2, H_2S, CO
Composting [92–94]	Except persistent pollutants	60 %	40–60 %	Temperature, MC, pH, carbon dioxide, oxygen, C/N ratio, nutrient content, volume reduction, bulk density, and water consumption	4–5 weeks	$50	5.5–8.0	Microorganisms maintain the heat required for composting	Produce 4 to 8 MJ heat per kg	Humus, CH_4, NH_2 and CO_2
Landfill [95–99]	Solid waste, household waste	95–96 %	64.5 %	A bottom liner, a cover, a leachate collection system, and the natural hydrogeologic setting	30 days–50 Years	28–67 €	3.7–6.5	Zero energy input	45 m^3 LFG/ton waste	Landfill gas,Biogas, CO_2, CH_4, N_2O, Leachate, nitrogen, oxygen, ammonia, sulfides, hydrogen
Incineration [100–102]	MSW	80–90 %	40–60 %	Feed rate (waste), temperatures of the Primary Combustion Chamber (PCC) and Secondary Combustion Chamber (SCC), fuel and combustion air consumption	Depending on the nature of waste	130 €	7.21–11.8	Waste-heat boilers and direct-contact water-spray quenches	500 to 600 kWh of electricity per ton of waste	CO_2 and water vapor, particulate matter, lead, mercury, dioxins, and furans
Pyrolysis [103–105]	Synthetic polymers and plastics	90 %	<20–25 %	Require absence of oxygen, temperature, time, heating rate, catalyst, size of biomass particles, and moisture content of biomass	~1 s to 1 day	$0.2 Million	5.52–10.10	20kw/h electricity required to process 1 ton of waste	Produce heat, bio-oil, and Biochar.	solid (charcoal, Biochar), liquid and non-condensable gases (H_2, CH4, C_nH_m, CO, CO_2, and NH_x), light alcohols, aldehydes, ketones, and organic acids
Gasification [106–108]	Organic carbonaceous feedstocks	Up to 95 %	5–35 %	Temperature, gasifying medium like equivalence ratio, residence time, reactor types, air stoichiometric ratio	<1 h	$40–80	4–10	4–6 MJ/Nm^3	12–28 MJ/Nm^3	H_2, CO, CH_4, CO_2, light hydrocarbons, syngas, water vapors, N_2, ash and tar
Hydrothermal Carbonization [109,110]	Organic waste and residual biomass	Up to 90 % %	75–90 %	Temperature, residence time, water-to-feedstock ratio, pH, pressure	60 min	$117	2–12	HTC requires 20 % of the electrical energy and approximately 70 % of the thermal energy as input	13–30 MJ/kg	Hydrochar, coal tar, fuel oils,
Torrefaction [111–114]	Pine, ash wood, Miscanthus, wheat straw, etc.	Up to 90 %	20–50 %	Reaction temperature, Heating rate, reactor environment, atmospheric pressure, residence time	2 min to 1 h	$164	5.0–9.0	5.2 to 14.1 MJ/kg	18–24 MJ/kg	Biochar, Solid coal fuel, CO_2, CO, H_2O
Liquefaction [115–117]	Microalgae	–	>80 %	low temperature, high H_2 pressure	1–180 min	$125	4.0–6.2	The liquefaction process uses 100 MJ/kg of heat	Output products are used as a heat source	Bio-oil, Biochar, C, N, and P nutrients
Black soldier fly larvae [118–120]	All most everything	75 %	60–75 %	Temperature, Moisture content, pH, Waste ratio, Light intensity, humidity, salinity	4–5 weeks	$6–16	5.6–8.0	Lower energy consumption	BSFL acts as an energy source	Humus, biodiesel, protein, grease, CO_2, BSFL frass and waste leftovers

-:no value available.

Table 2
Primary, secondary pollution and greenhouse gasses emission by mismanagement of waste.

Technology	Primary Pollutant	Secondary Pollutant	GHG	Atmospheric Pollution	Water Pollution
Anaerobic Digestion [121]	–	–	CH_4, CO_2, N_2O	NO_x, CO, SO_2	Phosphorus
Composting [122]	–	–	O_2, CO_2, CH_4, NO_x, N_2O, NH_3	NH_3, CH_4, N_2O, Odors and Dust	Leachate, NO_3^-, NH_4^+, organic compounds and PO_4^{3-}
Landfill [123–127]	nitrogen, oxygen, ammonia, sulfides, hydrogen	Polycyclic Aromatic Hydrocarbons	N_2O, NO_x, NH_3, CH_4, CO_2	CO, NO_x., SO_2	Heavy metals
Incineration [113,128]	Cadmium, lead, mercury, chromium, arsenic, and beryllium	Particulate matter, metals, acid gases, oxides of nitrogen, and sulfur	CH_4, CO_2, N_2O, NO_x, NH_3	Dioxins, furans	Dioxins, lead, and mercury
Pyrolysis [77,129]	Higher hydrocarbons	–	CH_4, CO_2, CO, N_2O, NH_3	CO, NO_x, SO_2	–
Gasification [130,131]	–	hydrocarbon oils, char, and ash	CH_4, N_2O, NH_3, CO_2, CO, H_2	NO_x, SO_2, CO, PM (Particulate matter)	–
Torrefaction [132]	–	–	CO_2, CO, CH_4, NH_3, N_2O	N_2O, NO_x, PM	Hg, Cl^-
BSFL [,133]	–	–	CH_4, CO_2, NH_3, N_2O		Larva frass and waste leftovers

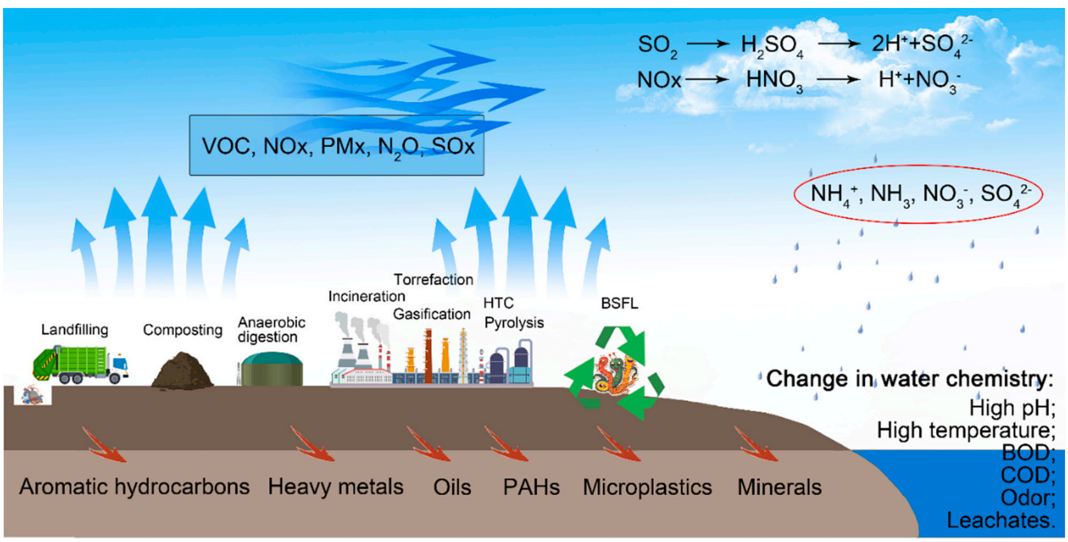

Fig. 6. Atmospheric, soil, and water chemistry change by mismanagement of waste.

approach to waste management, with trash being controlled within the broader context of environmental protection laws (the Environmental Management Act of 2002 in the Netherlands and the 1982 Pollution Control Act and 2004 Waste Regulations in Norway) [151]. Since joining the European Union, Poland, Estonia, Hungary, the Czech Republic, and Slovenia have all revised their waste laws.

In contrast, several laws governing waste management in Colombia and Israel might lead to loopholes or discrepancies. Recent advancements in the control of hazardous waste are examples of how Colombia's waste laws have progressed over the last several decades to include most elements of waste management [152]. In the same way, the Council of Australian Governments (COAG) adopted Australia's first national waste management plan in 1992 as part of the national strategy for ecologically sustainable development, which aimed to increase resource efficiency, decrease the adverse environmental impacts of waste disposal, and improve manage hazardous wastes by preventing their production and finding solutions to clean them up [153]. Thus, a waste management policy can be built, as shown in Fig. 7, aligning with the successful policies of some countries described below.

To promote responsible material recycling and avoid contamination from dangerous chemicals in such wastes, the European Union passed the Directive on Waste Electrical and Electronic Equipment and the Directive on the Restriction of Hazardous Substances (RoHS) in 2002 [154]. There is now a landfill tax in place in the United Kingdom, and it will grow from its current rate of 40 GBP (Great British Pound)/t to 180 GBP/t in 2023. In Italy, approximately 15 % of municipalities, encompassing 29 % of the country's total population, are presently covered by this kind of system that employs economic measures, such as a unit-based fee system where a management fee is paid based on the amount of waste discharged [2].

Waste Disposal and Public Cleansing Law (amended in 2010) and Law for the Promotion of Effective Utilities of Resources (2001) is the primary law governing the recycling of waste materials in Japan [155]. In addition, 2001, the Law on Promoting Green Purchasing was passed to encourage the public sector to buy recycled goods. The Waste Management Act (as revised in 2007) and the Act on Promotion of Resources Saving and Recycling form the backbone of Korea's waste management legal system (amended in 2008). Neighborhood opposition to developing waste treatment plants in Korea was the primary impetus for adopting 3R rules (Reduce, Reuse, Recycle). Requirements for trash recycling, a deposit system, and incineration and disposal regulations were all enacted under the Waste Management Act's 1991 full-text amendment [156]. The basic plan for material reuse, the fee system for waste treatment, rules on using one-way packaging and goods, and extended producer responsibility are all laid out in the Act on Promotion of Resources Saving and Recycling [157].

The Environmental Protection Law of the People's Republic of China (1989) is the foundational piece of environmental legislation in China. There was a change to the Environmental Pollution Prevention and Control Law regarding solid waste in 2005 [158]. It mandated not just a

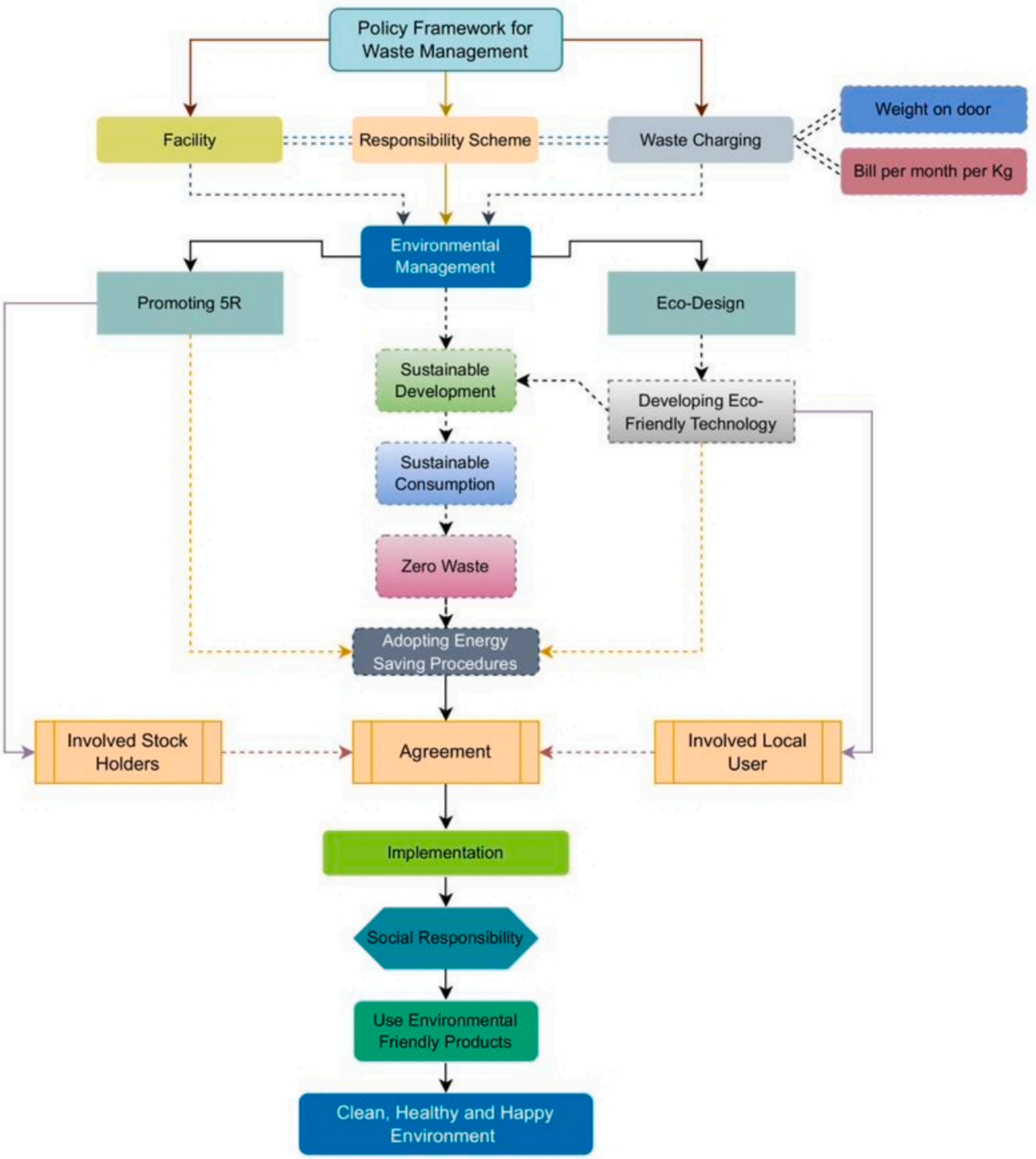

Fig. 7. Proposed policy framework for sustainable waste management inspired by international strategies.

decrease in the volume of the garbage but also the dangers due to waste by instituting 5R regulations, which adds "Refuse" and "Rethink" to the 3R, for MSW, industrial, and hazardous wastes [159]. In 2008, China passed the Circular Economy Promotion Law, the country's guiding legislation for waste management and recycling. Inadequate resources, inefficient use of recycled materials, and a national policy of solving the issue of resource depletion, together with the need for sustainable economic development, all contributed to the passing of the Circular Economy Promotion Law [160]. To rephrase, China has increased its usage of recycled materials due to a severe scarcity of resources amidst a fast-expanding economy. To realize the full potential of the Circular Economy Promotion Law, it is necessary to improve recycling and waste treatment methods and the financial stability of businesses that rely on recycled materials [161]. Although the issue of resource depletion and sustaining fast economic expansion has been at the forefront of China's waste management policy, the country's environmental protection system regarding imported recycling materials also needs changes [162]. Moreover, actions have to be taken against the rise in MSWthat has resulted from urbanization and rising incomes. The End-of-Life Vehicles (ELV) Recycling Law (2001) and the Waste Management Ordinance (2009) were enacted to facilitate this goal [163]. Due to China's enormous rise in automotive manufacturing, ELV is expected to skyrocket shortly. Nonetheless, the ELV Recycling Law prioritizes the prohibition of unlawful remodeling, maintains vehicle safety, and encourages new models with the environmentally friendly features above, assuring good waste management [164].

The Environmental Protection Law (as revised in 2005) is Vietnam's primary environmental law and supersedes any conflicting regulations on trash disposal. The system for handling trash was put in place by the decree on Solid Waste Management (SWM), which mandates safety precautions to be taken while dealing with garbage [165]. To reduce the need for landfills and hence the use of land, the decree requires comprehensive waste management that places a premium on recycling, reusing, treating and recovering garbage [166]. Garbage collection, transportation and treatment fees range from 40,000 VND (Vietnamese đồng)/t for MSW) to as high as 6,000,000 VND/t for hazardous waste. According to the national strategy for integrated SWM sets goals for Vietnam between 2025 and 2050 [167], in urban regions, all solid wastes from commercial operations and all hazardous and nonhazardous wastes from industrial sectors must be handled ecologically responsibly. In contrast, 90 % of all construction and MSWs must be collected in suburban areas for solid wastes, promoting 3R policies and using modern and ecologically sound procedures to reduce the quantity of ultimate disposal.

The African Waste Management Strategy (2019) and the African Circular Economy Alliance Framework (2020) provide the continental policy foundation for sustainable waste management, emphasizing circular economy principles and resource efficiency. Morocco has made significant legislative progress aligned with these frameworks, notably through its National Household Waste Recovery Program (PNVDM) launched in 2023, which aims to increase municipal solid waste recycling rates from 7 % in 2020 to 25 % by 2034 [168]. Supported by a $250 million World Bank financing package, Morocco is upgrading waste recovery infrastructure, closing uncontrolled dumpsites, and promoting waste-derived fuels in cement plants to reduce landfill dependency. Technologies in use include waste sorting centers, biomethanation for organic waste, and advanced landfill management [169]. Organic waste constitutes up to 70 % of total waste in some regions, with current recycling and treatment rates reaching approximately 63 % of total waste processed, reflecting a major focus on organic waste valorization. The government also targets expanding operational sorting centers from 15 by 2025 to 25 by 2030 to strengthen the sorting-recycling-recovery system [170].

In Europe, waste management practices are underpinned by comprehensive legislative frameworks and advanced technological systems, with countries such as France, Belgium, and Germany demonstrating exemplary models. France's approach is structured around key legislative instruments, notably the Waste Elimination Law of 1992 and the 2015 Energy Transition for Green Growth Law, which mandates a 10 % reduction in household waste relative to 2010 levels and sets a target of recycling 55 % of municipal waste by 2025 [171]. The integration of automated pneumatic waste collection systems, particularly in Paris and neighboring municipalities, has significantly reduced waste collection-related emissions and traffic congestion by up to 80 %, serving over 36,000 residents. As of 2023, France achieved a municipal waste recycling rate of 42.2 %, with plans to implement nationwide separate collection of biowaste by 2025 to enhance organic waste valorization. For example, Belgium's waste governance is characterized by stringent regional regulations, including the Brussels Capital Region Waste Ordinance, which mandates source separation and selective collection of priority waste streams. The country reported an 80 % recycling rate for packaging waste in 2022, with particularly high recycling rates for glass (98 %) and metals (96 %) [172]. The widespread deployment of organic waste converter machines and composting systems at both municipal and community levels supports efficient biowaste management and contributes to the development of a circular economy. Additionally, Germany operates within a highly structured regulatory environment, guided by the Circular Economy Act and the Closed Substance Cycle and Waste Management Act [174]. These frameworks enforce waste separation and operationalize the waste hierarchy of prevention, reuse, recycling, and energy recovery. Germany's municipal waste recycling rate exceeds 66 %, with residual landfilling limited to approximately 1 %. The Green Dot system plays a critical role in incentivizing the design and use of recyclable packaging materials. Furthermore, the country employs state-of-the-art sorting technologies and AI-driven analytical tools to optimize material recovery processes. Organic waste treatment through anaerobic digestion and composting transforms food and garden waste into biogas and high-quality compost, thereby facilitating resource circularity.

5. Conclusion

Sustainable waste management is a critical component in addressing environmental degradation and mitigating environmental pollution and reducing greenhouse gas (GHG) emissions. This review has comparatively assessed various waste management technologies, emphasizing their respective environmental impacts. Landfilling remains the most environmentally burdensome, primarily due to its high GHG emissions, followed by composting and anaerobic digestion, while thermochemical processes such as incineration, pyrolysis, and hydrothermal carbonization (HTC), while effective in volume reduction, generate secondary pollutants and may degrade the quality of residual products like compost. Among these, black soldier fly larvae (BSFL) treatment has emerged as a promising and sustainable strategy for organic waste valorization. By effectively reducing emissions of N_2O, NH_3, and CH_4, BSFL processing significantly reduces emissions of CH_4, NH_3, and particularly N_2O, thereby offering a lower environmental footprint while generating protein-rich biomass and nutrient-dense by-products that align well with the principles of a circular economy. Current data suggest that BSFL can reduce organic waste volume by approximately 33.3 %, supporting its potential for large-scale application. However, critical knowledge gaps remain concerning the influence of substrate composition, larval density, and rearing conditions on GHG emission profiles, especially for nitrous oxide (N_2O). Future research should emphasize real-time gas monitoring, standardized experimental protocols, and advanced analytical techniques to improve emission estimates and enhance the sustainability of BSFL-based waste treatment. Elucidating the mechanistic pathways of gas generation will be essential for optimizing BSFL systems and ensuring their alignment with international climate mitigation goals and sustainable development frameworks.

Justification for another review on this topic

Despite the existing reviews on biowaste management technologies, most focus on individual methods rather than a holistic comparison of their environmental footprints. Moreover, limited reviews integrate emerging technologies such as BSFL, hydrothermal carbonization, and microbial fuel cells into a comparative framework. Our review offers a fresh perspective by:

- Providing a comparative environmental impact assessment based on empirical data.
- Addressing key research gaps in sustainable biowaste management.
- Highlighting emerging technologies with high potential for circular economy integration.
- Offering actionable insights for policymakers and researchers to optimize waste valorization strategies.

Given the rapid evolution of waste management technologies and the growing global emphasis on climate change mitigation, this review aligns with the objectives of *Environmental chemistry and ecotoxicology* in advancing environmental sustainability research.

CRediT authorship contribution statement

Muhammad Salam: Writing – original draft. **Valentina Grossule:** Supervision. **Samia Elouali:** Funding acquisition, Conceptualization, Formal analysis, Writing – original draft. **Fayuan Wang:** Conceptualization. **Samira Benali:** Funding acquisition, Conceptualization, Formal analysis, Writing – review & editing. **Jean-Marie Raquez:** Conceptualization, Funding acquisition, Writing – review & editing. **Wael Yakti:** Investigation. **Viviana Bolletta:** Resources. **Mia Henjak:** Conceptualization. **Faisal Hayat:** Visualization. **Quanlong Wang:** Conceptualization.

Declaration of competing interest

The authors have declared no potential conflicts of interest concerning the study, authorship, and article publication.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: (Muhammad salam reports was provided by Padua university. Muhammad salam reports a relationship with Padua university that includes: funding grants. Nothings If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.)

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Appendix A. List of up to five related papers by the authors

1. **Grossule, V.,** & Stegmann, R. (2020). PROBLEMS IN TRADITIONAL LANDFILLING AND PROPOSALS FOR SOLUTIONS BASED ON SUSTAINABILITY. *Detritus*, *12*, 78–91. Doi: 10.31025/2611-4135/2020.14000
2. **Elouali, S.,** Ait Hamdan, Y., Benali, S., Lhomme, P., Gosselin, M., Raquez, J. M., & Rhazi, M. (2025). Extraction of chitin and chitosan from Hermetia illucens breeding waste: A greener approach for industrial application. *International Journal of Biological Macromolecules*, *285*, 138302. Doi: 10.1016/J.IJBIOMAC.2024.138302
3. Elouali, S., Ait Hamdan, Y., Belmajdoub, M., Rhazi, M., (2024). Green chitosan extraction from Hermetia illucens breeding waste (prepupal cases): Characterization and bioadsorption activity. International Journal of Biological Macromolecules, 281, 136449. Doi: 10.1016/J.IJIBIOMAC.2024.136449
4. **Salam, M.,** Alam, F., Dezhi, S., Nabi, G., Shahzadi, A., Hassan, S. U., Ali, M., Saeed, M. A., Hassan, J., Ali, N., & Bilal, M. (2021). Exploring the role of Black Soldier Fly Larva technology for sustainable management of municipal solid waste in developing countries. *Environmental Technology & Innovation*, *24*, 101934. Doi: 10.1016/j.eti.2021.101934
5. Lavagnolo, M. C., **Grossule, V.,** & Cossu, R. (2023). *Landfill Disposal in Developing Countries* (pp. 23–38). Doi: 10.1007/978-3-031-28001-6_2

Appendix B. List of Up to Five Related Papers by the Authors

1. Anshassi, M., Smallwood, T., & Townsend, T. G. (2022). Life cycle GHG emissions of MSW landfilling versus Incineration: Expected outcomes based on US landfill gas collection regulations. *Waste Management*, *142*, 44–54. Doi: 10.1016/j.wasman.2022.01.040
2. Czekała, W., Drozdowski, J., & Łabiak, P. (2023). Modern Technologies for Waste Management: A Review. *Applied Sciences*, *13*(15), 8847. Doi: 10.3390/app13158847
3. Gómez-Sanabria, A., Kiesewetter, G., Klimont, Z., Schoepp, W., & Haberl, H. (2022). Potential for future reductions of global GHG and air pollutants from circular waste management systems. *Nature Communications*, *13*(1), 106. Doi: 10.1038/s41467-021-27624-7
4. Liu, Y., Chen, S., Chen, A. Y., & Lou, Z. (2021). Variations of GHG emission patterns from waste disposal processes in megacity Shanghai from 2005 to 2015. *Journal of Cleaner Production*, *295*, 126338. Doi: 10.1016/j.jclepro.2021.126338
5. Monni, S. (2012). From landfilling to waste incineration: Implications on GHG emissions of different actors. *International Journal of Greenhouse Gas Control*, *8*, 82–89. Doi: 10.1016/J.IJGGC.2012.02.003

Appendix C. Justification for Another Review on This Topic

Despite the existing reviews on biowaste management technologies, most focus on individual methods rather than a holistic comparison of their environmental footprints. Moreover, limited reviews integrate emerging technologies such as BSFL, hydrothermal carbonization, and microbial fuel cells into a comparative framework. Our review offers a fresh perspective by:

- Providing a comparative environmental impact assessment based on empirical data.
- Addressing key research gaps in sustainable biowaste management.
- Highlighting emerging technologies with high potential for circular economy integration.
- Offering actionable insights for policymakers and researchers to optimize waste valorization strategies.

Given the rapid evolution of waste management technologies and the growing global emphasis on climate change mitigation, this review aligns with the objectives of *Environmental chemistry and ecotoxicology* in advancing environmental sustainability research.

References

[1] T.A. Kurniawan, C. Meidiana, M.H. Dzarfan Othman, H.H. Goh, K.W. Chew, Strengthening waste recycling industry in Malang (Indonesia): lessons from waste management in the era of industry 4.0, J. Clean. Prod. 382 (2023) 135296, https://doi.org/10.1016/j.jclepro.2022.135296.

[2] S. Nanda, F. Berruti, A technical review of bioenergy and resource recovery from municipal solid waste, J. Hazard. Mater. 403 (2021) 123970, https://doi.org/10.1016/J.JHAZMAT.2020.123970.

[3] J.D. Sachs, G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, J. Rockström, Six transformations to achieve the sustainable development goals, Nat. Sustain. 2 (2019) 805–814, https://doi.org/10.1038/s41893-019-0352-9.

[4] S. Fritz, L. See, T. Carlson, M. Haklay, J.L. Oliver, D. Fraisl, R. Mondardini, M. Brocklehurst, L.A. Shanley, S. Schade, U. Wehn, T. Abrate, J. Anstee, S. Arnold, M. Billot, J. Campbell, J. Espey, M. Gold, G. Hager, S. He, L. Hepburn, A. Hsu, D. Long, J. Masó, I. McCallum, M. Muniafu, I. Moorthy, M. Obersteiner, A. J. Parker, M. Weisspflug, S. West, Citizen science and the United Nations sustainable development goals, Nat. Sustain. 2 (2019) 922–930, https://doi.org/10.1038/s41893-019-0390-3.

[5] A.C. Gurgel, J.E.A. Seabra, S.M. Arantes, M.M.R. Moreira, L.R. Lynd, R. Galindo, Contribution of double-cropped maize ethanol in Brazil to sustainable development, Nat. Sustain. (2024), https://doi.org/10.1038/s41893-024-01424-5.

[6] Y. Li, S. Zhang, C. Liu, Research on greenhouse gas emission characteristics and emission mitigation potential of municipal solid waste treatment in Beijing, Sustainability 14 (2022) 8398, https://doi.org/10.3390/su14148398.

[7] Z. Zhang, M.Z. Malik, A. Khan, N. Ali, S. Malik, M. Bilal, Environmental impacts of hazardous waste, and management strategies to reconcile circular economy

and eco-sustainability, Sci. Total Environ. 807 (2022) 150856, https://doi.org/10.1016/j.scitotenv.2021.150856.
[8] Y. Liu, S. Chen, A.Y. Chen, Z. Lou, Variations of GHG emission patterns from waste disposal processes in megacity Shanghai from 2005 to 2015, J. Clean. Prod. 295 (2021) 126338, https://doi.org/10.1016/j.jclepro.2021.126338.
[9] United Nations, The Sustainable Development Goals Report. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf, 2020 (accessed November 27, 2024).
[10] B. Mei, H. Yue, X. Zheng, W.H. McDowell, Q. Zhao, Z. Zhou, Z. Yao, Effects of grazing pattern on ecosystem respiration and methane flux in a sown pasture in Inner Mongolia, China, Atmosphere (Basel) 10 (2018) 5, https://doi.org/10.3390/atmos10010005.
[11] T.V. Ramachandra, H.A. Bharath, G. Kulkarni, S.S. Han, Municipal solid waste: generation, composition and GHG emissions in Bangalore, India, Renew. Sust. Energ. Rev. 82 (2018) 1122–1136, https://doi.org/10.1016/J.RSER.2017.09.085.
[12] S. Siva Raman, L.C. Stringer, N.C. Bruce, C.S. Chong, Opportunities, challenges and solutions for black soldier fly larvae-based animal feed production, J. Clean. Prod. 373 (2022) 133802, https://doi.org/10.1016/j.jclepro.2022.133802.
[13] G. Ferrari, Z. Shi, F. Marinello, A. Pezzuolo, From biogas to biomethane: comparison of sustainable scenarios for upgrading plant location based on greenhouse gas emissions and cost assessments, J. Clean. Prod. 478 (2024) 143936, https://doi.org/10.1016/J.JCLEPRO.2024.143936.
[14] R. Amen, J. Hameed, G. Albashar, H.W. Kamran, M.U. Hassan Shah, M.K. U. Zaman, A. Mukhtar, S. Saqib, S.I. Ch, M. Ibrahim, S. Ullah, A.G. Al-Sehemi, S. R. Ahmad, J.J. Klemeš, A. Bokhari, S. Asif, Modelling the higher heating value of municipal solid waste for assessment of waste-to-energy potential: a sustainable case study, J. Clean. Prod. 287 (2021) 125575, https://doi.org/10.1016/j.jclepro.2020.125575.
[15] J.E. Castellanos-Sánchez, F.A. Aguilar-Aguilar, R. Hernández-Altamirano, J. A. Venegas Venegas, D. Raj Aryal, Biogas purification processes: review and prospects, Biofuels 15 (2024) 215–227, https://doi.org/10.1080/17597269.2023.2223801.
[16] Y. Abbas, S. Yun, Z. Wang, Y. Zhang, X. Zhang, K. Wang, Recent advances in bio-based carbon materials for anaerobic digestion: a review, Renew. Sust. Energ. Rev. 135 (2021) 110378, https://doi.org/10.1016/j.rser.2020.110378.
[17] M. Mainardis, M. Buttazzoni, F. Gievers, C. Vance, F. Magnolo, F. Murphy, D. Goi, Life cycle assessment of sewage sludge pretreatment for biogas production: from laboratory tests to full-scale applicability, J. Clean. Prod. 322 (2021) 129056, https://doi.org/10.1016/J.JCLEPRO.2021.129056.
[18] P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.O. Pörtner, D. Roberts, Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, 2019.
[19] L. Feng, A.J. Ward, V. Moset, H.B. Møller, Methane emission during on-site pre-storage of animal manure prior to anaerobic digestion at biogas plant: effect of storage temperature and addition of food waste, J. Environ. Manag. 225 (2018) 272–279, https://doi.org/10.1016/j.jenvman.2018.07.079.
[20] R.T. Weligama Thuppahige, S. Babel, Environmental impact assessment of organic fraction of municipal solid waste treatment by anaerobic digestion in Sri Lanka, Waste Manage. Res.: J. Sustain. Circul. Econ. 40 (2022) 236–243, https://doi.org/10.1177/0734242X211013405.
[21] Y. Van Fan, J.J. Klemeš, C.T. Lee, S. Perry, Anaerobic digestion of municipal solid waste: energy and carbon emission footprint, J. Environ. Manag. 223 (2018) 888–897, https://doi.org/10.1016/j.jenvman.2018.07.005.
[22] W. Sun, X. Wang, J.F. DeCarolis, M.A. Barlaz, Evaluation of optimal model parameters for prediction of methane generation from selected U.S. landfills, Waste Manag. 91 (2019) 120–127, https://doi.org/10.1016/J.WASMAN.2019.05.004.
[23] D. Liu, M. Zeppilli, M. Villano, Cees Buisman, A. Ter Heijne, Methane Production at Biocathodes, Bioelectrosynthesis, Wiley, in, 2020, pp. 129–159, https://doi.org/10.1002/9783527343829.ch5.
[24] A. Kaushal, M.P. Sharma, Methane emission from Panki open dump site of Kanpur, India, Procedia, Environ. Sci. 35 (2016) 337–347, https://doi.org/10.1016/J.PROENV.2016.07.014.
[25] R. Bian, T. Zhang, F. Zhao, J. Chen, C. Liang, W. Li, Y. Sun, X. Chai, X. Fang, L. Yuan, Greenhouse gas emissions from waste sectors in China during 2006–2019: implications for carbon mitigation, Process Saf. Environ. Prot. 161 (2022) 488–497, https://doi.org/10.1016/j.psep.2022.03.050.
[26] S. Panigrahi, B.K. Dubey, A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste, Renew. Energy 143 (2019) 779–797, https://doi.org/10.1016/j.renene.2019.05.040.
[27] Z. Wang, L. Geng, Carbon emissions calculation from municipal solid waste and the influencing factors analysis in China, J. Clean. Prod. 104 (2015) 177–184, https://doi.org/10.1016/j.jclepro.2015.05.062.
[28] H.K. Khuntia, A. Paliwal, D.R. Kumar, H.N. Chanakya, Review on solid-state anaerobic digestion of lignocellulosic biomass and organic solid waste, Environ. Monit. Assess. 194 (2022) 514, https://doi.org/10.1007/s10661-022-10160-2.
[29] S. Monni, From landfilling to waste incineration: implications on GHG emissions of different actors, Intern. J. Greenhouse Gas Contr. 8 (2012) 82–89, https://doi.org/10.1016/J.IJGGC.2012.02.003.
[30] S. Naidoo, A. Olaniran, Treated wastewater effluent as a source of microbial pollution of surface water resources, Int. J. Environ. Res. Public Health 11 (2013) 249–270, https://doi.org/10.3390/ijerph110100249.
[31] A. Rim-Rukeh, An assessment of the contribution of municipal solid waste dump sites fire to atmospheric pollution, Open J. Air Pollut. 03 (2014) 53–60, https://doi.org/10.4236/ojap.2014.33006.
[32] M. Anshassi, T. Smallwood, T.G. Townsend, Life cycle GHG emissions of MSW landfilling versus incineration: expected outcomes based on US landfill gas collection regulations, Waste Manag. 142 (2022) 44–54, https://doi.org/10.1016/j.wasman.2022.01.040.
[33] C. Nai, M. Tang, Y. Liu, Y. Xu, L. Dong, J. Liu, Q. Huang, Potentially contamination and health risk to shallow groundwater caused by closed industrial solid waste landfills: site reclamation evaluation strategies, J. Clean. Prod. 286 (2021) 125402, https://doi.org/10.1016/j.jclepro.2020.125402.
[34] S. Xue, L. Zhou, M. Zhong, M. Kumar Awasthi, H. Mao, Bacterial agents affected bacterial community structure to mitigate greenhouse gas emissions during sewage sludge composting, Bioresour. Technol. 337 (2021) 125397, https://doi.org/10.1016/j.biortech.2021.125397.
[35] S. Barrington, Effect of carbon source on compost nitrogen and carbon losses, Bioresour. Technol. 83 (2002) 189–194, https://doi.org/10.1016/S0960-8524(01)00229-2.
[36] X. Ren, Z. Wang, M. Zhao, J. Xie, Z. Zhang, F. Yang, Q. Wang, Y. Ding, Role of selenite on the nitrogen conservation and greenhouse gases mitigation during the goat manure composting process, Sci. Total Environ. 838 (2022) 155799, https://doi.org/10.1016/j.scitotenv.2022.155799.
[37] E. Krasny, S. Klarić, A. Korjenić, Analysis and comparison of environmental impacts and cost of bio-based house versus concrete house, J. Clean. Prod. 161 (2017) 968–976, https://doi.org/10.1016/j.jclepro.2017.05.103.
[38] C. Girón-Rojas, E. Gil, A. Garcia-Ruiz, N. Iglesias, M. López, Assessment of biowaste composting process for industrial support tool development through macro data approach, Waste Manag. 105 (2020) 364–372, https://doi.org/10.1016/j.wasman.2020.02.019.
[39] S. Mahapatra, Md.H. Ali, K. Samal, Assessment of compost maturity-stability indices and recent development of composting bin, Energy Nexus 6 (2022) 100062, https://doi.org/10.1016/j.nexus.2022.100062.
[40] M.K. Nguyen, C. Lin, H.G. Hoang, P. Sanderson, B.T. Dang, X.T. Bui, N.S. H. Nguyen, D.-V.N. Vo, H.T. Tran, Evaluate the role of biochar during the organic waste composting process: a critical review, Chemosphere 299 (2022) 134488, https://doi.org/10.1016/j.chemosphere.2022.134488.
[41] C.V. Preble, S.S. Chen, T. Hotchi, M.D. Sohn, R.L. Maddalena, M.L. Russell, N. J. Brown, C.D. Scown, T.W. Kirchstetter, Air pollutant emission rates for dry anaerobic digestion and composting of organic municipal solid waste, Environ. Sci. Technol. 54 (2020) 16097–16107, https://doi.org/10.1021/acs.est.0c03953.
[42] C. Qi, R. Yin, J. Cheng, Z. Xu, J. Chen, X. Gao, G. Li, L. Nghiem, W. Luo, Bacterial dynamics for gaseous emission and humification during bio-augmented composting of kitchen waste with lime addition for acidity regulation, Sci. Total Environ. 848 (2022) 157653, https://doi.org/10.1016/j.scitotenv.2022.157653.
[43] Y. Li, X. Zhao, Y. Li, X. Li, Waste incineration industry and development policies in China, Waste Manag. 46 (2015) 234–241, https://doi.org/10.1016/j.wasman.2015.08.008.
[44] H. Mao, H. Zhang, Q. Fu, M. Zhong, R. Li, B. Zhai, Z. Wang, L. Zhou, Effects of four additives in pig manure composting on greenhouse gas emission reduction and bacterial community change, Bioresour. Technol. 292 (2019) 121896, https://doi.org/10.1016/j.biortech.2019.121896.
[45] Y. Fukumoto, K. Suzuki, T. Osada, K. Kuroda, D. Hanajima, T. Yasuda, K. Haga, Reduction of nitrous oxide emission from pig manure composting by addition of nitrite-oxidizing Bacteria, Environ. Sci. Technol. 40 (2006) 6787–6791, https://doi.org/10.1021/es0611801.
[46] A. Hongthong, S. Nakapan, Assessing the impact of a waste incinerator on the environment using the MAIAC-AOD and AERMOD models, Front. Environ. Sci. 11 (2023), https://doi.org/10.3389/fenvs.2023.1240705.
[47] J. Zhu, R. Li, Z. Wang, S. Liu, H. Lv, Decoupled analysis of the effect of hydroxyl functional groups on delay of ignition with fictitious hydroxyl, Process Saf. Environ. Prot. 161 (2022) 285–294, https://doi.org/10.1016/J.PSEP.2022.03.028.
[48] T. Astrup, J. Møller, T. Fruergaard, Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions, Waste Manage. Res.: J. Sustain. Circul. Econ. 27 (2009) 789–799, https://doi.org/10.1177/0734242X09343774.
[49] J. Slavík, O. Potluka, K. Rybová, Subsidies in waste management: effective instruments or a cul-de-sac of European structural policies? Waste Manag. 65 (2017) 1–2, https://doi.org/10.1016/j.wasman.2017.05.040.
[50] W. Li, K. Gu, Q. Yu, Y. Sun, Y. Wang, M. Xin, R. Bian, H. Wang, Y. Wang, D. Zhang, Leaching behavior and environmental risk assessment of toxic metals in municipal solid waste incineration fly ash exposed to mature landfill leachate environment, Waste Manag. 120 (2021) 68–75, https://doi.org/10.1016/j.wasman.2020.11.020.
[51] J.M. Fernández-González, A.L. Grindlay, F. Serrano-Bernardo, M.I. Rodríguez-Rojas, M. Zamorano, Economic and environmental review of waste-to-energy systems for municipal solid waste management in medium and small municipalities, Waste Manag. 67 (2017) 360–374, https://doi.org/10.1016/J.WASMAN.2017.05.003.
[52] K. Volkart, C. Bauer, C. Boulet, Life cycle assessment of carbon capture and storage in power generation and industry in Europe, Intern. J. Greenhouse Gas Contr. 16 (2013) 91–106, https://doi.org/10.1016/J.IJGGC.2013.03.003.
[53] F. Güleç, O. Williams, E.T. Kostas, A. Samson, E. Lester, A comprehensive comparative study on the energy application of chars produced from different biomass feedstocks via hydrothermal conversion, pyrolysis, and torrefaction,

Energy Convers. Manag. 270 (2022) 116260, https://doi.org/10.1016/J.ENCONMAN.2022.116260.
[54] D. Gahane, D. Biswal, S.A. Mandavgane, Life cycle assessment of biomass pyrolysis, Bioenergy Res. 15 (2022) 1387–1406, https://doi.org/10.1007/s12155-022-10390-9.
[55] N. Mehta, A. Anderson, C.R. Johnston, D.W. Rooney, Evaluating the opportunity for utilising anaerobic digestion and pyrolysis of livestock manure and grass silage to decarbonise gas infrastructure: a Northern Ireland case study, renew, Energy 196 (2022) 343–357, https://doi.org/10.1016/J.RENENE.2022.06.115.
[56] S. Spatari, V. Larnaudie, I. Mannoh, M.C. Wheeler, N.A. Macken, C.A. Mullen, A. A. Boateng, Environmental, exergetic and economic tradeoffs of catalytic- and fast pyrolysis-to-renewable diesel, renew, Energy 162 (2020) 371–380, https://doi.org/10.1016/j.renene.2020.08.042.
[57] F. Dorado, P. Sanchez, A. Alcazar-Ruiz, L. Sanchez-Silva, Fast pyrolysis as an alternative to the valorization of olive mill wastes, J. Sci. Food Agric. 101 (2021) 2650–2658, https://doi.org/10.1002/jsfa.10856.
[58] D. Özçimen, F. Karaosmanoğlu, Production and characterization of bio-oil and biochar from rapeseed cake, Renew. Energy 29 (2004) 779–787, https://doi.org/10.1016/J.RENENE.2003.09.006.
[59] S. Karnjanakom, P. Maneechakr, Designs of linear-quadratic regression models for facile conversion of carbohydrate into high value (5-(ethoxymethyl)furan-2-carboxaldehyde) fuel chemical, Energy Convers. Manag. 196 (2019) 410–417, https://doi.org/10.1016/J.ENCONMAN.2019.06.015.
[60] M. Balat, Use of biomass sources for energy in Turkey and a view to biomass potential, Biomass Bioenergy 29 (2005) 32–41, https://doi.org/10.1016/J.BIOMBIOE.2005.02.004.
[61] X. Zhuang, J. Liu, Q. Zhang, C. Wang, H. Zhan, L. Ma, A review on the utilization of industrial biowaste via hydrothermal carbonization, Renew. Sust. Energ. Rev. 154 (2022) 111877, https://doi.org/10.1016/j.rser.2021.111877.
[62] F. Dai, S. Zhang, Y. Luo, K. Wang, Y. Liu, X. Ji, Recent Progress on hydrogen-rich syngas production from coal gasification, Processes 11 (2023) 1765, https://doi.org/10.3390/pr11061765.
[63] D. Xiang, P. Li, L. Liu, Concept design, technical performance, and GHG emissions analysis of petroleum coke direct chemical looping hydrogen highly integrated with gasification for methanol production process, Sci. Total Environ. 838 (2022) 156652, https://doi.org/10.1016/j.scitotenv.2022.156652.
[64] C. Liptow, A.-M. Tillman, M. Janssen, Life cycle assessment of biomass-based ethylene production in Sweden — is gasification or fermentation the environmentally preferable route? Int. J. Life Cycle Assess. 20 (2015) 632–644, https://doi.org/10.1007/s11367-015-0855-1.
[65] H. Zhao, X. Zhang, S. Zhang, W. Chen, D. Tong, A. Xiu, Effects of agricultural biomass burning on regional haze in China: a review, Atmosphere (Basel) 8 (2017) 88, https://doi.org/10.3390/atmos8050088.
[66] Y. Wang, Y. Yang, Research on greenhouse gas emissions and economic assessment of biomass gasification power generation technology in China Based on LCA method, Sustainability 14 (2022) 16729, https://doi.org/10.3390/su142416729.
[67] T.A. Khan, A.S. Saud, S.S. Jamari, M.H.A. Rahim, J.-W. Park, H.-J. Kim, Hydrothermal carbonization of lignocellulosic biomass for carbon rich material preparation: a review, Biomass Bioenergy 130 (2019) 105384, https://doi.org/10.1016/j.biombioe.2019.105384.
[68] A. Waheed, S. Naqvi, I. Ali, Co-torrefaction progress of biomass residue/waste obtained for high-value bio-solid products, Energies (Basel) 15 (2022) 8297, https://doi.org/10.3390/en15218297.
[69] H. Xu, S. Cheng, D. Hungwe, K. Yoshikawa, F. Takahashi, Co-pyrolysis coupled with torrefaction enhances hydrocarbons production from rice straw and oil sludge: the effect of torrefaction on co-pyrolysis synergistic behaviors, Appl. Energy 327 (2022) 120104, https://doi.org/10.1016/J.APENERGY.2022.120104.
[70] Q. Wang, S. Wu, D. Cui, H. Zhou, D. Wu, S. Pan, F. Xu, Z. Wang, Co-hydrothermal carbonization of organic solid wastes to hydrochar as potential fuel: a review, Sci. Total Environ. 850 (2022) 158034, https://doi.org/10.1016/j.scitotenv.2022.158034.
[71] R. Yahav Spitzer, V. Mau, A. Gross, Using hydrothermal carbonization for sustainable treatment and reuse of human excreta, J. Clean. Prod. 205 (2018) 955–963, https://doi.org/10.1016/J.JCLEPRO.2018.09.126.
[72] T.G. Bridgeman, J.M. Jones, I. Shield, P.T. Williams, Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties, Fuel 87 (2008) 844–856, https://doi.org/10.1016/J.FUEL.2007.05.041.
[73] T. Wang, Y. Zhai, Y. Zhu, C. Li, G. Zeng, A review of the hydrothermal carbonization of biomass waste for hydrochar formation: process conditions, fundamentals, and physicochemical properties, Renew. Sust. Energ. Rev. 90 (2018) 223–247, https://doi.org/10.1016/J.RSER.2018.03.071.
[74] C. Rodriguez Correa, M. Bernardo, R.P.P.L. Ribeiro, I.A.A.C. Esteves, A. Kruse, Evaluation of hydrothermal carbonization as a preliminary step for the production of functional materials from biogas digestate, J. Anal. Appl. Pyrolysis 124 (2017) 461–474, https://doi.org/10.1016/j.jaap.2017.02.014.
[75] M.A. Waheed, O.A. Akogun, C.C. Enweremadu, An overview of torrefied bioresource briquettes: quality-influencing parameters, enhancement through torrefaction and applications, Bioresour. Bioprocess. 9 (2022) 122, https://doi.org/10.1186/s40643-022-00608-1.
[76] X. He, A.K. Lau, S. Sokhansanj, C. Jim Lim, X.T. Bi, S. Melin, Dry matter losses in combination with gaseous emissions during the storage of forest residues, Fuel 95 (2012) 662–664, https://doi.org/10.1016/J.FUEL.2011.12.027.
[77] J. Chen, X. Ma, Z. Yu, T. Deng, X. Chen, L. Chen, M. Dai, A study on catalytic co-pyrolysis of kitchen waste with tire waste over ZSM-5 using TG-FTIR and Py-GC/MS, Bioresour. Technol. 289 (2019) 121585, https://doi.org/10.1016/j.biortech.2019.121585.
[78] L.I. Fajimi, J. Chrisostomou, B.O. Oboirien, A techno-economic analysis (TEA) of a combined process of torrefaction and gasification of lignocellulose biomass (bagasse) for methanol and electricity production, Biomass Convers. Biorefinery 14 (2024) 12501–12516, https://doi.org/10.1007/s13399-022-03499-6.
[79] W. Kajina, P. Rousset, W.H. Chen, T. Sornpitak, J.M. Commandré, Coupled effect of torrefaction and blending on chemical and energy properties for combustion of major open burned agriculture residues in Thailand, Renew. Energy 118 (2018) 113–121, https://doi.org/10.1016/J.RENENE.2017.11.006.
[80] C. Pedrazzani, L. Righi, F. Vescovi, L. Maistrello, A. Caligiani, Black soldier fly as a new chitin source: extraction, purification and molecular/structural characterization, LWT 191 (2024) 115618, https://doi.org/10.1016/j.lwt.2023.115618.
[81] S. Elkadaoui, M. Azzi, J. Desbrieres, J. Zim, Y. El Hachimi, A. Tolaimate, Valorization of Hermetia illucens breeding rejects by chitins and chitosans production. Influence of processes and life cycle on their physicochemical characteristics, Int. J. Biol. Macromol. 266 (2024) 131314, https://doi.org/10.1016/J.IJBIOMAC.2024.131314.
[82] M. Elsayed, J. Wang, H. Wang, Z. Zhou, A.I. Osman, A.W. Almutairi, S. Faisal, A. Abomohra, Conversion of protein-rich waste into biodiesel by Hermetia illucens: enhanced energy recovery and reduced greenhouse gas emissions, Sustain Energy Technol Assess 66 (2024) 103825, https://doi.org/10.1016/j.seta.2024.103825.
[83] W. Yang, M. Yang, H. Wen, Y. Jiao, Global warming potential of CH4 uptake and N2O emissions in saline–alkaline soils, Atmos. Environ. 191 (2018) 172–180, https://doi.org/10.1016/J.ATMOSENV.2018.08.017.
[84] A. Parodi, I.J.M. De Boer, W.J.J. Gerrits, J.J.A. Van Loon, M.J.W. Heetkamp, J. Van Schelt, J.E. Bolhuis, H.H.E. Van Zanten, Bioconversion efficiencies, greenhouse gas and ammonia emissions during black soldier fly rearing – a mass balance approach, J. Clean. Prod. 271 (2020) 122488, https://doi.org/10.1016/j.jclepro.2020.122488.
[85] T. McEachern, Determining Heat Production of Black Solderi Fly Determining Heat Production of Black Solderi Fly Larvae, Larvae, Hermetia Illucens, to Design Rearing, to Design Rearing Structures at Livestock Facilities Structures at Livestock Facilities, 2018, https://doi.org/10.13023/etd.2018.479.
[86] X. Xiao, P. Jin, L. Zheng, M. Cai, Z. Yu, J. Yu, J. Zhang, Effects of black soldier fly (*Hermetia illucens*) larvae meal protein as a fishmeal replacement on the growth and immune index of yellow catfish (*Pelteobagrus fulvidraco*), Aquac. Res. 49 (2018) 1569–1577, https://doi.org/10.1111/are.13611.
[87] A. Mertenat, S. Diener, C. Zurbrügg, Black soldier fly biowaste treatment – assessment of global warming potential, Waste Manag. 84 (2019) 173–181, https://doi.org/10.1016/J.WASMAN.2018.11.040.
[88] K.A. Boakye-Yiadom, A. Ilari, D. Duca, Greenhouse gas emissions and life cycle assessment on the black soldier Fly (*Hermetia illucens* L.), Sustainability 14 (2022) 10456, https://doi.org/10.3390/su141610456.
[89] M. Skovgaard, N. Hedal, A. Villanueva, F.M. Andersen, H. Larsen, Municipal Waste Management and Greenhouse Gases. http://waste.eionet.europa.eu/, 2008.
[90] P. Mosharraf, M.S. Zahan, D.K. Das, S. Chowdhury, Biogas potentiality through waste management in Bangladesh, J. Renew. Energy Environ. 7 (2020) 44–49, https://doi.org/10.30501/jree.2020.222856.1089.
[91] A.D. Singh, A. Upadhyay, S. Shrivastava, V. Vivekanand, Life-cycle assessment of sewage sludge-based large-scale biogas plant, Bioresour. Technol. 309 (2020) 123373, https://doi.org/10.1016/j.biortech.2020.123373.
[92] G.M. Shah, N. Tufail, H.F. Bakhat, I. Ahmad, M. Shahid, H.M. Hammad, W. Nasim, A. Waqar, M. Rizwan, R. Dong, Composting of municipal solid waste by different methods improved the growth of vegetables and reduced the health risks of cadmium and lead, Environ. Sci. Pollut. Res. 26 (2019) 5463–5474, https://doi.org/10.1007/s11356-018-04068-z.
[93] H. Hettiarachchi, J.N. Meegoda, S. Ryu, Organic waste buyback as a viable method to enhance sustainable municipal solid waste Management in Developing Countries, Int. J. Environ. Res. Public Health 15 (2018) 2483, https://doi.org/10.3390/ijerph15112483.
[94] H. Hettiarachchi, S. Ryu, S. Caucci, R. Silva, Municipal solid waste Management in Latin America and the Caribbean: issues and potential solutions from the governance perspective, Recycling 3 (2018) 19, https://doi.org/10.3390/recycling3020019.
[95] K.P. Gopinath, D.-V.N. Vo, D. Gnana Prakash, A. Adithya Joseph, S. Viswanathan, J. Arun, Environmental applications of carbon-based materials: a review, Environ. Chem. Lett. 19 (2021) 557–582, https://doi.org/10.1007/s10311-020-01084-9.
[96] R. Katakojwala, H. Kopperi, S. Kumar, S. Venkata Mohan, Hydrothermal liquefaction of biogenic municipal solid waste under reduced H2 atmosphere in biorefinery format, Bioresour. Technol. 310 (2020) 123369, https://doi.org/10.1016/J.BIORTECH.2020.123369.
[97] M.T. Munir, I. Mardon, S. Al-Zuhair, A. Shawabkeh, N.U. Saqib, Plasma gasification of municipal solid waste for waste-to-value processing, Renew. Sust. Energ. Rev. 116 (2019) 109461, https://doi.org/10.1016/J.RSER.2019.109461.
[98] S. Nanda, F. Berruti, Municipal solid waste management and landfilling technologies: a review, Environ. Chem. Lett. 19 (2021) 1433–1456, https://doi.org/10.1007/s10311-020-01100-y.

[99] I.A. Tałałaj, P. Biedka, I. Bartkowska, Treatment of landfill leachates with biological pretreatments and reverse osmosis, Environ. Chem. Lett. 17 (2019) 1177–1193, https://doi.org/10.1007/s10311-019-00860-6.
[100] D. Blasenbauer, F. Huber, J. Lederer, M.J. Quina, D. Blanc-Biscarat, A. Bogush, E. Bontempi, J. Blondeau, J.M. Chimenos, H. Dahlbo, J. Fagerqvist, J. Giro-Paloma, O. Hjelmar, J. Hyks, J. Keaney, M. Lupsea-Toader, C.J. O'Caollai, K. Orupõld, T. Pająk, F.-G. Simon, L. Svecova, M. Šyc, R. Ulvang, K. Vaajasaari, J. Van Caneghem, A. van Zomeren, S. Vasarevičius, K. Wégner, J. Fellner, Legal situation and current practice of waste incineration bottom ash utilisation in Europe, Waste Manag. 102 (2020) 868–883, https://doi.org/10.1016/j.wasman.2019.11.031.
[101] F. Huber, D. Blasenbauer, P. Aschenbrenner, J. Fellner, Complete determination of the material composition of municipal solid waste incineration bottom ash, Waste Manag. 102 (2020) 677–685, https://doi.org/10.1016/j.wasman.2019.11.036.
[102] H. Luo, Y. Cheng, D. He, E.-H. Yang, Review of leaching behavior of municipal solid waste incineration (MSWI) ash, Sci. Total Environ. 668 (2019) 90–103, https://doi.org/10.1016/j.scitotenv.2019.03.004.
[103] S. Zhou, H. Liang, L. Han, G. Huang, Z. Yang, The influence of manure feedstock, slow pyrolysis, and hydrothermal temperature on manure thermochemical and combustion properties, Waste Manag. 88 (2019) 85–95, https://doi.org/10.1016/J.WASMAN.2019.03.025.
[104] J. Alvarez, M. Amutio, G. Lopez, J. Bilbao, M. Olazar, Fast co-pyrolysis of sewage sludge and lignocellulosic biomass in a conical spouted bed reactor, Fuel 159 (2015) 810–818, https://doi.org/10.1016/j.fuel.2015.07.039.
[105] Y. Yang, Z. Wei, X. Zhang, X. Chen, D. Yue, Q. Yin, L. Xiao, L. Yang, Biochar from Alternanthera philoxeroides could remove pb(II) efficiently, Bioresour. Technol. 171 (2014) 227–232, https://doi.org/10.1016/J.BIORTECH.2014.08.015.
[106] J. Cai, R. Zeng, W. Zheng, S. Wang, J. Han, K. Li, M. Luo, X. Tang, Synergistic effects of co-gasification of municipal solid waste and biomass in fixed-bed gasifier, Process. Saf. Environ. Prot. 148 (2021) 1–12, https://doi.org/10.1016/J.PSEP.2020.09.063.
[107] S. Ge, P.N.Y. Yek, Y.W. Cheng, C. Xia, W.A. Wan Mahari, R.K. Liew, W. Peng, T.-Q. Yuan, M. Tabatabaei, M. Aghbashlo, C. Sonne, S.S. Lam, Progress in microwave pyrolysis conversion of agricultural waste to value-added biofuels: a batch to continuous approach, Renew. Sust. Energ. Rev. 135 (2021) 110148, https://doi.org/10.1016/j.rser.2020.110148.
[108] F.N. Rahma, C. Tamzysi, A. Hidayat, M.A. Adnan, Investigation of process parameters influence on municipal solid waste gasification with CO2 capture via process simulation approach, Intern. J. Renew. Energy Develop. 10 (2021) 1–10, https://doi.org/10.14710/ijred.2021.31982.
[109] N. Gao, Z. Li, C. Quan, N. Miskolczi, A. Egedy, A new method combining hydrothermal carbonization and mechanical compression in-situ for sewage sludge dewatering: bench-scale verification, J. Anal. Appl. Pyrolysis 139 (2019) 187–195, https://doi.org/10.1016/j.jaap.2019.02.003.
[110] A.L. Tasca, M. Puccini, R. Gori, I. Corsi, A.M.R. Galletti, S. Vitolo, Hydrothermal carbonization of sewage sludge: a critical analysis of process severity, hydrochar properties and environmental implications, Waste Manag. 93 (2019) 1–13, https://doi.org/10.1016/j.wasman.2019.05.027.
[111] R.S. Monisha, R.L. Mani, B. Sivaprakash, N. Rajamohan, D.-V.N. Vo, Green remediation of pharmaceutical wastes using biochar: a review, Environ. Chem. Lett. 20 (2022) 681–704, https://doi.org/10.1007/s10311-021-01348-y.
[112] V.S. Sikarwar, M. Pohořelý, E. Meers, S. Skoblia, J. Moško, M. Jeremiáš, Potential of coupling anaerobic digestion with thermochemical technologies for waste valorization, Fuel 294 (2021) 120533, https://doi.org/10.1016/J.FUEL.2021.120533.
[113] Z. Xing, Z. Ping, Z. Xiqiang, S. Zhanlong, W. Wenlong, S. Jing, M. Yanpeng, Applicability of municipal solid waste incineration (MSWI) system integrated with pre-drying or torrefaction for flue gas waste heat recovery, Energy 224 (2021) 120157, https://doi.org/10.1016/j.energy.2021.120157.
[114] Y. Yang, R.K. Liew, A.M. Tamothran, S.Y. Foong, P.N.Y. Yek, P.W. Chia, T. Van Tran, W. Peng, S.S. Lam, Gasification of refuse-derived fuel from municipal solid waste for energy production: a review, Environ. Chem. Lett. 19 (2021) 2127–2140, https://doi.org/10.1007/s10311-020-01177-5.
[115] N. Doctor, G. Parker, K. Vang, M. Smith, B. Kayan, Y. Yang, Stability and extraction of vanillin and coumarin under subcritical water conditions, Molecules 25 (2020) 1061, https://doi.org/10.3390/molecules25051061.
[116] S. Hao, S. Ren, N. Zhou, H. Chen, M. Usman, C. He, Q. Shi, G. Luo, S. Zhang, Molecular composition of hydrothermal liquefaction wastewater from sewage sludge and its transformation during anaerobic digestion, J. Hazard. Mater. 383 (2020) 121163, https://doi.org/10.1016/j.jhazmat.2019.121163.
[117] E. Ovsyannikova, A. Kruse, G.C. Becker, Feedstock-dependent phosphate recovery in a pilot-scale hydrothermal liquefaction bio-crude production, Energies (Basel) 13 (2020) 379, https://doi.org/10.3390/en13020379.
[118] J.C.F. Van, P.E. Tham, H.R. Lim, K.S. Khoo, J.-S. Chang, P.L. Show, Integration of internet-of-things as sustainable smart farming technology for the rearing of black soldier fly to mitigate food waste, J. Taiwan Inst. Chem. Eng. 137 (2022) 104235, https://doi.org/10.1016/j.jtice.2022.104235.
[119] C. Yang, S. Ma, F. Li, L. Zheng, J.K. Tomberlin, Z. Yu, J. Zhang, C. Yu, M. Fan, M. Cai, Characteristics and mechanisms of ciprofloxacin degradation by black soldier fly larvae combined with associated intestinal microorganisms, Sci. Total Environ. 811 (2022) 151371, https://doi.org/10.1016/j.scitotenv.2021.151371.
[120] S. Zhang, P. Xiong, Y. Ma, N. Jin, S. Sun, X. Dong, X. Li, J. Xu, H. Zhou, W. Xu, Transformation of food waste to source of antimicrobial proteins by black soldier fly larvae for defense against marine Vibrio parahaemolyticus, Sci. Total Environ. 826 (2022) 154163, https://doi.org/10.1016/J.SCITOTENV.2022.154163.
[121] G. Nahar, D. Mote, V. Dupont, Hydrogen production from reforming of biogas: review of technological advances and an Indian perspective, Renew. Sust. Energ. Rev. 76 (2017) 1032–1052, https://doi.org/10.1016/j.rser.2017.02.031.
[122] S. Kumar, S. Negi, A. Mandpe, R.V. Singh, A. Hussain, Rapid composting techniques in Indian context and utilization of black soldier fly for enhanced decomposition of biodegradable wastes - a comprehensive review, J. Environ. Manag. 227 (2018) 189–199, https://doi.org/10.1016/j.jenvman.2018.08.096.
[123] X. Luo, Q. Yang, Y. Lin, Z. Tang, J.K. Tomberlin, W. Liu, Y. Huang, Black soldier fly larvae effectively degrade lincomycin from pharmaceutical industry wastes, J. Environ. Manag. 307 (2022) 114539, https://doi.org/10.1016/j.jenvman.2022.114539.
[124] A.V. Luparelli, J.H. Saadoun, V. Lolli, C. Lazzi, S. Sforza, A. Caligiani, Dynamic changes in molecular composition of black soldier fly prepupae and derived biomasses with microbial fermentation, Food Chem. X 14 (2022) 100327, https://doi.org/10.1016/j.fochx.2022.100327.
[125] J.-J. Ma, C.-L. Jiang, X.-H. Tao, J.-L. Sheng, X.-Z. Sun, T.-Z. Zhang, Z.-J. Zhang, Insights on dissolved organic matter and bacterial community succession during secondary composting in residue after black soldier fly larvae (Hermetia illucens L.) bioconversion for food waste treatment, Waste Manag. 142 (2022) 55–64, https://doi.org/10.1016/j.wasman.2022.01.034.
[126] H. Mei, C. Li, X. Li, B. Hu, L. Lu, J.K. Tomberlin, W. Hu, Characteristics of tylosin and enrofloxacin degradation in swine manure digested by black soldier fly (Hermetia illucens L.) larvae, Environ. Pollut. 293 (2022) 118495, https://doi.org/10.1016/j.envpol.2021.118495.
[127] I.R. Mocharla, R. Selvam, V. Govindaraj, M. Muthu, Performance and life-cycle assessment of high-volume fly ash concrete mixes containing steel slag sand, Constr. Build. Mater. 341 (2022) 127814, https://doi.org/10.1016/j.conbuildmat.2022.127814.
[128] H. He, S. Lu, Y. Peng, M. Tang, M. Zhan, S. Lu, L. Xu, W. Zhong, L. Xu, Emission characteristics of dioxins during iron ore co-sintering with municipal solid waste incinerator fly ash in a sintering pot, Chemosphere 287 (2022) 131884, https://doi.org/10.1016/j.chemosphere.2021.131884.
[129] V. Chhabra, S. Bhattacharya, Y. Shastri, Pyrolysis of mixed municipal solid waste: characterisation, interaction effect and kinetic modelling using the thermogravimetric approach, Waste Manag. 90 (2019) 152–167, https://doi.org/10.1016/j.wasman.2019.03.048.
[130] U. Arena, Process and technological aspects of municipal solid waste gasification. A review, Waste Manag. 32 (2012) 625–639, https://doi.org/10.1016/J.WASMAN.2011.09.025.
[131] J.C. Bandara, R. Jaiswal, H.K. Nielsen, B.M.E. Moldestad, M.S. Eikeland, Air gasification of wood chips, wood pellets and grass pellets in a bubbling fluidized bed reactor, Energy 233 (2021) 121149, https://doi.org/10.1016/j.energy.2021.121149.
[132] G.K. Parku, F.-X. Collard, J.F. Görgens, Pyrolysis of waste polypropylene plastics for energy recovery: influence of heating rate and vacuum conditions on composition of fuel product, Fuel Process. Technol. 209 (2020) 106522, https://doi.org/10.1016/j.fuproc.2020.106522.
[133] S.A. Siddiqui, B. Ristow, T. Rahayu, N.S. Putra, N. Widya Yuwono, K. Nisa, B. Mategeko, S. Smetana, M. Saki, A. Nawaz, A. Nagdalian, Black soldier fly larvae (BSFL) and their affinity for organic waste processing, Waste Manag. 140 (2022) 1–13, https://doi.org/10.1016/J.WASMAN.2021.12.044.
[134] P. Ghisellini, C. Cialani, S. Ulgiati, A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, J. Clean. Prod. 114 (2016) 11–32, https://doi.org/10.1016/J.JCLEPRO.2015.09.007.
[135] C. Stigsson, E. Furusjö, P. Börjesson, A model of an integrated hydrothermal liquefaction, gasification and Fischer-Tropsch synthesis process for converting lignocellulosic forest residues into hydrocarbons, Bioresour. Technol. 353 (2022) 126070, https://doi.org/10.1016/J.BIORTECH.2021.126070.
[136] V. Paolini, F. Petracchini, M. Segreto, L. Tomassetti, N. Naja, A. Cecinato, Environmental impact of biogas: a short review of current knowledge, J. Environ. Sci. Health A 53 (2018) 899–906, https://doi.org/10.1080/10934529.2018.1459076.
[137] C. Qi, R. Yin, X. Gao, J. Chen, R. Wang, Z. Xu, W. Luo, G. Li, Y. Li, Development of solid-state anaerobic digestion and aerobic composting hybrid processes for organic solid waste treatment and resource recovery: a review, Curr. Pollut. Rep. 8 (2022) 221–233, https://doi.org/10.1007/s40726-022-00223-w.
[138] S.L. Narnaware, N.L. Panwar, Biomass gasification for climate change mitigation and policy framework in India: a review, Bioresour. Technol. Rep. 17 (2022) 100892, https://doi.org/10.1016/j.biteb.2021.100892.
[139] A. Erdiwansyah, R. Mamat Gani, M. Bahagia, S. Nizar, M.H. Mat Yana, Muhibbuddin Yasin, S.M. Rosdi, Prospects for renewable energy sources from biomass waste in Indonesia, Case Stud. Chem. Environ.l Eng. 10 (2024) 100880, https://doi.org/10.1016/J.CSCEE.2024.100880.
[140] Y.C. Chan, R.K. Sinha, Weijin Wang, emission of greenhouse gases from home aerobic composting, anaerobic digestion and vermicomposting of household wastes in Brisbane (Australia), Waste Manage. Res.: J. Sustain. Circul. Econ. 29 (2011) 540–548, https://doi.org/10.1177/0734242X10375587.
[141] Y.C. Chen, Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology, J. Clean. Prod. 192 (2018) 262–269, https://doi.org/10.1016/J.JCLEPRO.2018.04.260.
[142] G.A. Kristanto, W. Koven, Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia, City Environ. Interact. 4 (2019) 100027, https://doi.org/10.1016/J.CACINT.2020.100027.
[143] P.S. Michel Devadoss, P. Agamuthu, S.B. Mehran, C. Santha, S.H. Fauziah, Implications of municipal solid waste management on greenhouse gas emissions

in Malaysia and the way forward, Waste Manag. 119 (2021) 135–144, https://doi.org/10.1016/J.WASMAN.2020.09.038.

[144] Z. Hameed, M. Aslam, Z. Khan, K. Maqsood, A.E. Atabani, M. Ghauri, M. S. Khurram, M. Rehan, A.-S. Nizami, Gasification of municipal solid waste blends with biomass for energy production and resources recovery: current status, hybrid technologies and innovative prospects, Renew. Sust. Energ. Rev. 136 (2021) 110375, https://doi.org/10.1016/j.rser.2020.110375.

[145] J. Čespiva, L. Niedzwiecki, M. Wnukowski, K. Krochmalny, J. Mularski, T. Ochodek, H. Pawlak-Kruczek, Torrefaction and gasification of biomass for polygeneration: production of biochar and producer gas at low load conditions, Energy Rep. 8 (2022) 134–144, https://doi.org/10.1016/J.EGYR.2022.10.081.

[146] M. Saidi, M.H. Gohari, A.T. Ramezani, Hydrogen production from waste gasification followed by membrane filtration: a review, Environ. Chem. Lett. 18 (2020) 1529–1556, https://doi.org/10.1007/s10311-020-01030-9.

[147] M. Batista, R. Goyannes Gusmão Caiado, O.L. Gonçalves Quelhas, G. Brito Alves Lima, W. Leal Filho, I.T. Rocha Yparraguirre, A framework for sustainable and integrated municipal solid waste management: barriers and critical factors to developing countries, J. Clean. Prod. 312 (2021) 127516, https://doi.org/10.1016/j.jclepro.2021.127516.

[148] A.E. Torkayesh, B. Malmir, M. Rajabi Asadabadi, Sustainable waste disposal technology selection: the stratified best-worst multi-criteria decision-making method, Waste Manag. 122 (2021) 100–112, https://doi.org/10.1016/J.WASMAN.2020.12.040.

[149] A.M.A. Saja, A.M.Z. Zimar, S.M. Junaideen, Municipal solid waste management practices and challenges in the Southeastern coastal cities of Sri Lanka, Sustainability 13 (2021) 4556, https://doi.org/10.3390/su13084556.

[150] R. Santagata, M. Ripa, A. Genovese, S. Ulgiati, Food waste recovery pathways: challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment, J. Clean. Prod. 286 (2021) 125490, https://doi.org/10.1016/J.JCLEPRO.2020.125490.

[151] A. Mafalda Matos, J. Sousa-Coutinho, Municipal solid waste incineration bottom ash recycling in concrete: preliminary approach with Oporto wastes, Constr. Build. Mater. 323 (2022) 126548, https://doi.org/10.1016/J.CONBUILDMAT.2022.126548.

[152] J. Zhang, A. Zhang, C. Huang, H. Yu, C. Zhou, Characterising the resilient behaviour of pavement subgrade with construction and demolition waste under Freeze–Thaw cycles, J. Clean. Prod. 300 (2021) 126702, https://doi.org/10.1016/J.JCLEPRO.2021.126702.

[153] L.H. Xavier, M. Ottoni, J. Lepawsky, Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks, J. Clean. Prod. 297 (2021) 126570, https://doi.org/10.1016/J.JCLEPRO.2021.126570.

[154] M. Yazdani, K. Kabirifar, B.E. Frimpong, M. Shariati, M. Mirmozaffari, A. Boskabadi, Improving construction and demolition waste collection service in an urban area using a simheuristic approach: a case study in Sydney, Australia, J. Clean. Prod. 280 (2021) 124138, https://doi.org/10.1016/J.JCLEPRO.2020.124138.

[155] D. Guzzo, V.P. Rodrigues, J. Mascarenhas, A systems representation of the circular economy: transition scenarios in the electrical and electronic equipment (EEE) industry, Technol. Forecast. Soc. Change 163 (2021) 120414, https://doi.org/10.1016/j.techfore.2020.120414.

[156] G. Di Foggia, M. Beccarello, Designing waste management systems to meet circular economy goals: the Italian case, Sustain. Prod. Consum. 26 (2021) 1074–1083, https://doi.org/10.1016/J.SPC.2021.01.002.

[157] I. D'Adamo, P.M. Falcone, D. Huisingh, P. Morone, A circular economy model based on biomethane: what are the opportunities for the municipality of Rome and beyond? Renew. Energy 163 (2021) 1660–1672, https://doi.org/10.1016/J.RENENE.2020.10.072.

[158] M.G. Davidson, R.A. Furlong, M.C. McManus, Developments in the life cycle assessment of chemical recycling of plastic waste – a review, J. Clean. Prod. 293 (2021) 126163, https://doi.org/10.1016/J.JCLEPRO.2021.126163.

[159] K.S. Al-Mawali, A.I. Osman, A.H. Al-Muhtaseb, N. Mehta, F. Jamil, F. Mjalli, G. R. Vakili-Nezhaad, D.W. Rooney, Life cycle assessment of biodiesel production utilising waste date seed oil and a novel magnetic catalyst: a circular bioeconomy approach, Renew. Energy 170 (2021) 832–846, https://doi.org/10.1016/j.renene.2021.02.027.

[160] G. Yadav, S. Luthra, S.K. Jakhar, S.K. Mangla, D.P. Rai, A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: an automotive case, J. Clean. Prod. 254 (2020) 120112, https://doi.org/10.1016/j.jclepro.2020.120112.

[161] K. Parajuly, C. Fitzpatrick, O. Muldoon, R. Kuehr, Behavioral change for the circular economy: a review with focus on electronic waste management in the EU, Resourc. Conserv. Recycl.: X 6 (2020) 100035, https://doi.org/10.1016/J.RCRX.2020.100035.

[162] H.S. Ng, P.E. Kee, H.S. Yim, P.-T. Chen, Y.-H. Wei, J. Chi-Wei Lan, Recent advances on the sustainable approaches for conversion and reutilization of food wastes to valuable bioproducts, Bioresour. Technol. 302 (2020) 122889, https://doi.org/10.1016/j.biortech.2020.122889.

[163] J. Lederer, A. Gassner, F. Kleemann, J. Fellner, Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna, Resour. Conserv. Recycl. 161 (2020) 104942, https://doi.org/10.1016/J.RESCONREC.2020.104942.

[164] K. Kabirifar, M. Mojtahedi, C. Wang, V.W.Y. Tam, Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: a review, J. Clean. Prod. 263 (2020) 121265, https://doi.org/10.1016/j.jclepro.2020.121265.

[165] M.S. Aslam, B. Huang, L. Cui, Review of construction and demolition waste management in China and USA, J. Environ. Manag. 264 (2020) 110445, https://doi.org/10.1016/J.JENVMAN.2020.110445.

[166] N.I. Sinthumule, S.H. Mkumbuzi, Participation in community-based solid waste Management in Nkulumane Suburb, Bulawayo, Zimbabwe, Resources 8 (2019) 30, https://doi.org/10.3390/resources8010030.

[167] A. Petryk, M. Malinowski, M. Dziewulska, S. Guzdek, The impact of the amount of fees for the collection and Management of Municipal Waste on the percentage of selectively collected waste, J. Ecol. Eng. 20 (2019) 46–53, https://doi.org/10.12911/22998993/112874.

[168] Moroccan Society's Uneven Response to the Proliferation of Waste this Case Study is an Analysis Carried out as Part of the Annual Synthesis Report on Sectoral Climate Action Download the Global Report and Other Case Studies at WWW.CLIMATE-CHANCE.ORG, n.d. https://maroc.ma/en/news/environment-moroccos-legislative-progress-reflects-its-commitment-aligning-its-legal-instruments (accessed June 5, 2025).

[169] L. Wissale, The "Zero Waste" Policy in Morocco. https://www.circemed.org/articles/h/the-zero-waste-policy-in-morocco.html, 2025.

[170] Environment: Morocco's Legislative Progress Reflects its Commitment to Aligning its Legal Instruments with International Standards - Justice Minister, Https://Maroc.Ma/En/News/Environment-Moroccos-Legislative-Progress-Reflects-Its-Commitment-Aligning-Its-Legal-Instruments (n.d.).

[171] A. Bruna, Recycling Rate of Municipal Waste in France from 2000 to 2023, Https://Www.Statista.Com/Statistics/632917/Municipal-Waste-Recycling-France/ (2025).

[172] European Environment Agency, Early Warning Assessment Related to the 2025 Targets for Municipal Waste and Packaging Waste in Belgium, 2022.