recycling

MDPI

Review

Circular Economy Approaches for Sustainable Waste Management: A Review on Integration of AI, Advanced Technologies and Policy Recommendations

Abhishek N. Srivastava [1], Arun Krishna Vuppaladadiyam [2], Rakhi Punnadan Koroth [1], Christoph Pfeifer [3], Ajay Kumar Kaviti [4], Jafar Fathi [5,6,7], Alan Maslani [5], Praveen Barmavatu [8], Maksym Buryi [5], Michael Pohorely [9] and Vineet Singh Sikarwar [5,9,*]

1 Department of Civil Engineering, National Institute of Technology Calicut, Kozhikode 673601, India
2 School of Civil and Mechanical Engineering, Curtin University, Perth, WA 6102, Australia
3 Institute of Chemical and Energy Engineering, BOKU University, 1180 Vienna, Austria
4 Department of Mechanical Engineering, Vallurupalli Nageswara Rao Vignana Jyothi Institute of Engineering and Technology (VNRVJIET), Hyderabad 500090, India
5 Institute of Plasma Physics of the Czech Academy of Sciences, Za Slovankou 1782/3, 182 00 Prague, Czech Republic
6 Department of Inorganic Chemistry, University of Chemistry and Technology Prague, Technická 5, 166 28 Prague, Czech Republic
7 Department of Environmental Geosciences, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, Suchdol, 165 00 Prague, Czech Republic
8 Departamento de Mecánica, Facultad de Ingeniería, Universidad Tecnológica Metropolitana, Av. José Pedro Alessandri 1242, Ñuñoa, Santiago 7810003, Chile
9 Department of Power Engineering, University of Chemistry and Technology, Technická 5, 166 28 Prague, Czech Republic
* Correspondence: sikarwar@ipp.cas.cz

Abstract

Landfilling remains the dominant waste disposal method worldwide, particularly in developing countries, posing serious environmental, health, and climate challenges. Inefficient practices, weak regulations, and un-engineered sites contribute to massive greenhouse gas (GHG) emissions and resource loss. Transitioning to a circular economy (CE) offers a transformative path for sustainable waste management. By closing material loops, recovering energy, urban mining, controlling emissions and CE strategies can convert traditional landfills into eco-efficient systems. The integration of artificial intelligence (AI) further enhances this transition, enabling real-time monitoring, predictive management, and optimized resource recovery, thereby maximizing environmental and economic benefits. This review presents a three-level CE framework at micro (individual organizations), meso (industrial networks), and macro (national and international) levels designed to extract maximum value from waste streams and mitigate climate impacts. The proposed strategies demonstrate the potential to drastically reduce GHG emissions, promote clean energy via waste-to-energy routes, and contribute to SDGs 7, 11, 12, 13 and 15. By combining technology, innovation, and strategic management, this work highlights how AI-driven CE approaches can transform landfills from environmental liabilities into engines of sustainability and climate action. In implementing CE strategies at various levels, various challenges including technological, socio-economic, ethical, policy-based, and unintended consequences are encountered which impact sustainability initiatives. This review comprehensively discusses challenges associated with CE implementation and identifies technological advancement, social awareness and data-driven AI/ML-based modeling which could ensure success in circularity and ultimately curb climate change impacts in the long term.

Check for updates

Academic Editor: Sha Liang

Received: 9 March 2026
Revised: 12 May 2026
Accepted: 25 May 2026
Published: 29 May 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Keywords: artificial intelligence; climate change; environmental pollution; landfill; material and resource recovery; SDGs-7, 11, 13; sustainable waste management

1. Introduction

Climate change refers to shifts in climate patterns caused by the accumulation of greenhouse gas (GHG) emissions. In recent decades, unprecedented GHG emissions have increased global surface temperatures, driving global warming and, as a consequence thereof, increasing the occurrence of environmental disasters such as flooding, avalanches, droughts and others. Such emissions originate from both natural systems such as volcanoes, wetlands, and oceans and human activities, including energy production, industrial operations, and land-use changes [1]. In a statistical analysis regarding emissions from natural and human sources, it has been found that natural sources can self-balance their emissions, but anthropogenic emissions burden the earth's system. The emissions gap report released by the United Nations Environment Programme (UNEP) in 2022 indicated that the total global GHG emissions between 2010 and 2019 averaged 54.4 Gt of CO_2e, including land use, land-use change and forestry (LULUCF). The GHG emissions, excluding LULUCF, in 2021 were estimated at 52.8 Gt CO_2e, slightly higher than in 2019 [1,2]. The United Nations Framework Convention on Climate Change (UNFCCC) consolidated a major agreement in 2015, popularly known as the Paris Agreement, to accelerate and intensify the actions needed to achieve a sustainable and low-carbon future [2]. The primary goal of the Paris Agreement is to pursue efforts to restrict the rise in global temperature to 1.5 °C [3]. Achieving such targets aligns with broader net-zero commitments and the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 11 (sustainable cities), and SDG 13 (climate action).

Climate change impacts human security and biodiversity by triggering heat waves, ocean warming and other repercussions. In the current scenario, waste management contributes considerably to GHG emissions and climate change. As per recent investigations reported in United Nations Environment Programme Global Environment Outlook (GEO-7) and Global Methane Assessment reports, municipal solid waste (MSW) handling significantly contributes to climate change through landfill methane emissions, open disposal and uncontrolled burning [4,5]. Methane escaped from landfills possesses considerably higher interim global warming potential (GWP) than carbon dioxide, thus reinforcing landfill disposal, biowaste processing, recycling, and other circular economy (CE) measures as vital factors in view of climate change mitigation and net-zero target frameworks. However, pragmatic application of technologies can unleash its immense potential to become an asset in the future [2,3]. The waste management sector's contribution towards climate change mitigation can occur in many ways. Indirect GHG emissions can be minimized by reducing the quantity of waste generated and increasing recycling opportunities [1,6]. A few strategies, such as anaerobic digestion (AD) of organic fractions, increased collection of landfill gas, and energy generation from landfill gases can reduce GHG emissions [6,7]. Importantly, integrated waste valorization using thermochemical and biological pathways under CE principles, which enables energy recovery and resource efficiency. Global waste generation is expected to increase dramatically, from 3.4 billion tons of MSW per year by 2050, a 70% rise compared to 2016 levels [7]. Asia generated about one-third of the global solid waste with China and India as the two prime contributors, with generation rates of 0–0.49 kg/capita/day and 0.5–0.9 kg/capita/day, respectively [8,9]. The anticipated increase in the overall global solid waste generation, including construction and demolition waste (CDW) and industrial wastes, is 7–10 billion tons per year. Unarguably, economic

growth and urbanization has triggered the generation of substantial quantities of solid waste which, if not properly handled, could pose serious environmental implications [10]. In countries with abundant land availability, landfilling is considered an economical method of solid waste disposal, although with inherent risks and challenges [11]. Recovering energy in the form of heat, fuel and electricity from MSW managing processes has recently gained immense attention [12–14]. Several pathways have been explored to recover energy from wastes, including thermal and hydrothermal process, recovery of gas from landfills, biohydrogen production from AD, etc. [15–18]. However, the choice of solid waste management approaches/technology strictly adheres to the policies and regulations of the local government.

In view of the rising population leading to exponential growth in solid waste generation, many countries across the globe have taken initiatives to promote a CE to mitigate the negative impacts associated with improper solid waste management. The CE strategies provide a framework for sustainable waste management by promoting closed loops (post-consumer recycling) and slowing loops (maintaining product value via repair, remanufacturing, and reuse) [19]. A CE is closely related to the 9Rs hierarchy, which includes refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover strategies [20]. It is worth noting that CE in solid waste management aims to achieve waste reduction, better resource utilization, and better management by shutting down material cycles that lead to input–output cycles. However, geographic benefits are attained by implementing more efficient material recycling processes and reverse logistics while strategically positioning close to municipal waste origins and potential industrial contributors [21]. For instance, in a recent study, the authors pointed out that it is necessary to have knowledge of local CE methodology to demonstrate environmental benefits and promote a total resource management chain [22]. A CE promotes eco-industrial initiatives and allows for economic development similar to natural systems with minimal environmental impacts and less energy and resource consumption.

To promote a CE, minimize waste reduction, and close material input–output cycles, nations across the globe have initiated policy frameworks. In the European Union (EU), the 7th Environmental Action Plan (EAP) was introduced in 2014, aiming to achieve 'zero waste emission' by 2030 [23,24]. However, the targets relevant to MSW in EU waste strategy were limited and included the diversion of biodegradable waste to landfills (Landfill Directive, 1999); recycling and preparation for recycling (Waste Framework Directive, 2008 and Packaging Waste Directive, 1994); and 75/442/EEC-Council Directive, later amended by 91/156/EEC (waste) and 91/689/EEC (hazardous waste) [23–28]. The EU has also reinforced its CE and climate change mitigation program with initiatives such as the European Green Deal and the updated Circular Economy Action Plan (CEAP) for prioritizing sustainable resource management, waste reduction, advanced recycling goals, and net-neutral corporate systems [29]. Such policies endorse Extended Producer Responsibility (EPR), eco-design practices in industries, sustainable product protocols, and compulsory CE implementation targets for specific wastes like plastics, batteries, and e-waste [29].

Similarly, in the United States, solid waste legislation is categorized under the Resource Conservation and Recovery Act (RCRA), enacted in 1976. Under Subtitle D of the RCRA, the solid waste program supports states in developing plans to manage non-hazardous industrial and MSWs. In addition, the act sets criteria for MSW landfills and prohibits open dumping [24]. However, it is to be noted that despite taking numerous precautionary measures and enabling robust policies and regulations, solid waste management and associated GHG emissions are still global issues. Undeniably, a sustainable solution to these issues is yet to be identified. It is believed that a CE approach would result in a

unified framework and establish a link between different treatment technologies, thereby promoting sustainable waste management with clean energy generation and material recovery coupled with reduced GHG emissions, which contributes in turn to SDGs 7, 11, 12, 13 and 15.

The structure of the review is as follows. In Section 1, an in-depth analysis of the contribution of landfills to GHG emissions and the necessary mitigation measures are provided. Section 2 defines and discusses the role of landfills in methane emissions and the pathways to minimize them. In Section 3, a special focus is placed on the CE to recover valuable materials and energy from solid waste. In addition, approaches to counter climate change with the CE approaches are presented. In Section 4, strategies that can be considered to reduce GHG emissions via recycling and waste reduction employing different technologies are discussed. Section 6 recommends a few initiatives to transform challenges into opportunities vis-à-vis waste management, climate change and resource recovery. The conceptual presentation of the entire work is depicted in Figure 1. Although previous studies have examined landfill emissions, recycling technologies, and CE models separately, very few provide an integrated framework linking landfill abatement, climate change mitigation, and CE strategies aligned with SDGs 7, 11, and 13. The novelty of this study lies in its three-stage CE-based solution (micro, meso, and macro levels), which offers a multi-scalar approach for transforming conventional landfills into sustainable resource hubs.

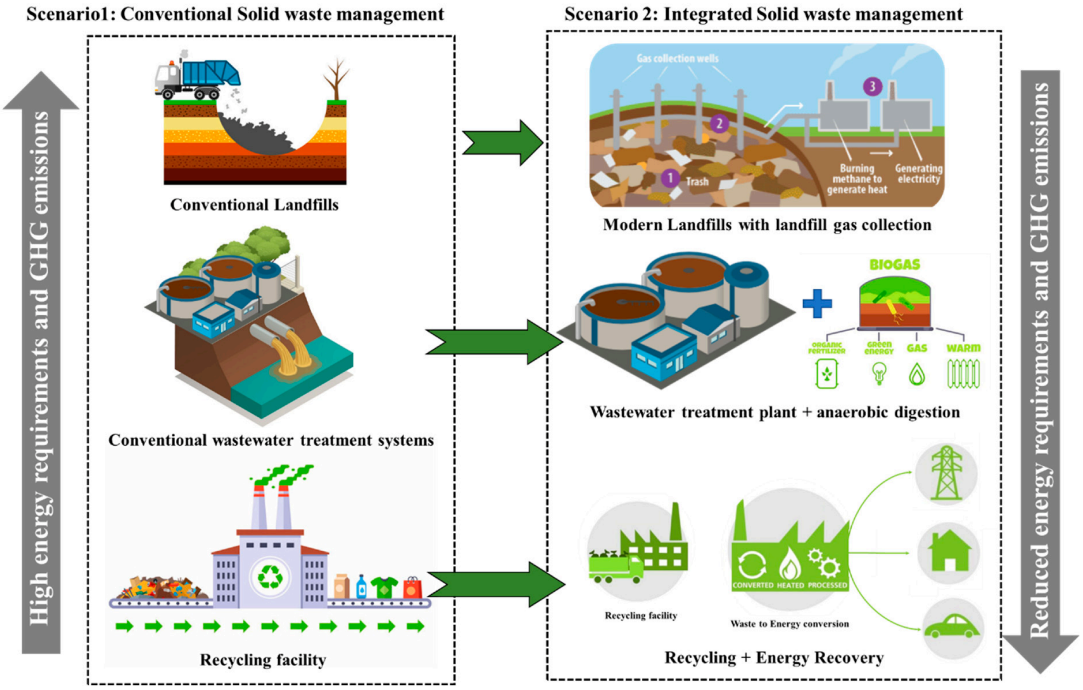


Figure 1. Schematic reflecting the link between integrated solid waste management and climate change due to GHG emissions.

Despite growing global attention towards CE-based waste management, net-zero transition, climate change mitigation and adaptation, the existing literature remains fragmented and isolated on (i) integrating lifecycle assessments into landfill-to-CE transitions, (ii) addressing social equity and governance issues, (iii) developing hybrid treatment systems combining biological and thermochemical pathways, (iv) artificial intelligence (AI) application in solid waste management, and (v) policy recommendation for CE measures implementation. Limited reviews are available on integrated discussion on all aforementioned aspects, including detailed discussion on different solid waste treatment technologies

within CE frameworks linking climate mitigation dimensions. Furthermore, vital execution issues—comprising lifecycle trade-offs, region wise MSW heterogeneity, techno-economic assessment, role of AI and data limitations, informal waste-sector incorporation, and exclusive wastes viz. e-waste and end-of-life renewable energy materials—persist, inadequately discussed in existing review articles. Also, this review directly addresses these gaps by proposing actionable strategies, highlighting governance challenges, and identifying opportunities for future research and innovation. This paper investigates the connection between landfills, CE applications, and climate change mitigation, with particular emphasis on GHG emissions from waste systems. Landfills exist as substantial sources of methane and carbon dioxide release, while ineffectiveness in waste handling and resource recovery continue to limit the environmental and economic performance of CE strategies. Although technologies such as waste-to-energy, advanced recycling, and biological treatment offer considerable potential to decrease emissions and recuperate value from MSW, their extensive espousal is restrained by technological, infrastructure, scalability, and socio-economic challenges. Recent developments in circular waste management progressively encourage integrated, multi-stage strategies that prioritize waste reduction, material recovery, and energy valorization in configuration with SDGs. This transition is increasingly supported by policy instruments such as EPR frameworks, landfill diversion targets, carbon-pricing mechanisms, and AI-enabled digital monitoring systems that facilitate sustainable waste governance and climate mitigation planning. Within this embryonic framework, AI shows promise as a vital enabler, supporting advanced waste characterization, augmented landfill operations, improved methane capture, and data-driven system management. By bridging the gap between policy aspirations and operational realities, AI-enabled CE strategies can simultaneously curb GHG emissions, enhance economic efficacy, and reinforce the resilience of waste management systems.

2. Relation Between Landfills and Climate Change

2.1. Landfill as a Source for GHG Emissions

Sanitary landfills are treatment and disposal systems manufactured to receive wastes and contain the by-products formed from biochemical degradation so that they do not pose a threat to environmental and human health [30]. Biodegradation during landfilling involves multiple decomposition reactions to form gases and leachate. In most developing countries and/or countries of the global south, landfills are one of the largest anthropogenic sources of environmental pollution, as the confinement of degradation products in engineered landfills is very challenging owing to unprecedented waste generation and operational issues [31]. In general, landfills experience anaerobic conditions for organic waste degradation, depending upon the type of landfilling, operational conditions, and waste properties. As the waste is disposed of in landfill cells, oxygen contacts the waste and initiates degradation, and entrapped oxygen in pores is partially released [32]. The anaerobic process starts upon consumption of trapped oxygen. The AD process in landfills involves four-staged degradation, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis [33]. The AD process relies on diverse microorganisms that perform degradation at the aforementioned levels. Hydrolysis is the initial process of breaking down complex organic waste polymers into relatively simpler biopolymers for further utilization by acidogenic bacteria. This is the rate-limiting step of the AD process [34]. During the acidogenesis process, the acidogenic microorganisms produce intermediate, volatile fatty acids (VFAs), which are converted to acetates during the acetogenesis phase. Further, such acetates and hydrogen produced in the third stage are utilized by methanogens to form methane gas.

Energy release during various waste degradation stages in landfills depends on intermediate gaseous components. During the AD process in landfills, the putrescible organic

matter is consumed by heterotrophic bacteria as a source of food and energy [34]. Among them, heterotrophic and chemoautotrophic bacteria utilize hydrocarbons as energy and CO_2 as carbon (food) sources [35]. The energy required for bacterial growth through redox reactions or catabolism is represented in Table 1. Depending upon the heterogeneity and composition of the disposed waste, these reactions may occur simultaneously or individually in a landfill. Even though the anaerobic processes or methanogenesis reactions release much less energy yield than aerobic respiration, methane possesses extraordinary greenhouse potential if released into an open environment [33]. Landfilled waste mass maintains mesophilic temperature (35 to 45 °C) because of biological heat generated during anaerobic decomposition. The biological heat generation is responsible for the carbon metabolism rate, thereby determining the efficacy of methane generation in landfills [31]. In various oxygen-free zones, denitrification and sulphate reduction also occur, resulting in nitrogen and sulfur dioxide as gaseous components of landfill gas [36]. However, the localized oxygen in waste mass carries forward oxidation for nearby organic mass and releases comparatively higher heat, precisely in the thermophilic (50 to 70 °C) range, thus achieving a higher valorization rate than the anaerobic process, but no methane production is attained.

Table 1. Biochemical redox reactions involved in landfill systems and their energy behavior.

Redox Biochemical Reactions	Oxidation	Reaction	Energy Yield (kcals/mol)	Reference
Aerobic respiration	O_2	$O_2 \Rightarrow CO_2$	689	[37]
Anaerobic reaction (methanogenesis)	CO_2	$H_2 + CO_2 \Rightarrow CH_4$	8.4	[38]
Denitrification	NO_3^-	$NO_3^- + H^+ \Rightarrow N_2$	649	[39]
Iron reduction	Fe^{3+}	$Fe_2(OH)_3 + 2H^+ \Rightarrow Fe^{2+}$	300	[40]
Sulphate reduction	SO_4^{2-}	$SO_4^{2-} + 2H^+ \Rightarrow HS^-$	190	[41]

Over the decades, landfills have emerged as significant anthropogenic contributors to climate change, accounting for nearly 5% of global greenhouse gas (GHG) emissions [42]. Biogas produced from the AD of landfilled waste typically consists of 55–60% methane (CH_4) and 40–45% carbon dioxide (CO_2) [43]. Specifically, landfill GHGs emissions, including CH_4, CO_2 and nitrous oxide (N_2O), contribute approximately 1–2% of total GHG emissions [42]. Additionally, the leachate treatment systems associated with landfills also generate CH_4 and N_2O [44]. Among all landfill gases, methane is particularly critical due to its quantity and high global warming potential (GWP). Since the preindustrial era, CH_4 has contributed nearly 30% of global warming and exerted 84–86 times the warming impact of CO_2 over almost 20 years [45]. Currently, the waste sector is responsible for 18% of global anthropogenic methane emissions as compared to fossil fuel extraction industries and AD, accounting for 24% and 27%, respectively [46]. MSW accounts for 11% of methane emissions. The current worldwide MSW generation is 2 billion metric tons, which is predicted to increase by 70% by 2050 due to population growth, increased consumerism and life standards [33]. Consequently, the accelerated MSW generation also has the potential to drive a proportionate increment in landfill gas, thereby corresponding to an increase in methane, as GHG would also contribute to global warming.

Landfill methane in the United States was nearly 122.4 million metric tons of CO_2 equivalent (MMT CO_2e) in 2021, compared to global landfill methane emission of 794 MMT CO_2e in 2005 [34]. Moreover, global anthropogenic emissions from MSW alone reflected a similar warming effect as nearly 4.4 billion metric tons of CO_2e (year 2020), which is equivalent to yearly emissions from ~950 million gasoline vehicles [47]. Further, Sun et al. [48] also compared the emissions generated by MSW landfills in China and Japan. The Chinese landfills produce higher CO_2 emissions than Japan's and recommended

stringent recycling policies for developing countries [18,49]. Even in engineered landfills equipped with gas collection systems, fugitive methane emission from cover cracks is still a major challenge [40]. Fugitive methane emission from landfills often remains as an unidentified GHG source since its quantification and prediction for development of efficient methane emission management system is challenging due to its high temporal and spatial variability. In particular, such emissions are dependent on climatological conditions, native topography, life and type of built cover system, waste characteristics underneath cover, and quality of supervision in the landfill site [50]. In a recent study, fugitive methane emissions from old historical landfills contributed ~901 tons/year of methane, which is considerably higher than that from natural gas repositories and manholes [51]. They further concluded that such emission from old landfills significantly impact socio-economic culture and suggested building an effective landfill gas recovery system; nevertheless, expected methane mitigation of ~600 tons might cost 7000–12,000 USD per ton [51]. Therefore, considering accelerating methane emissions, fugitive GHG emissions and its warming impact, landfill methane mitigation or its utilization for energy generation purposes is urgently needed.

2.2. Strategies to Curb Landfill Induced GHG Emissions

Limiting landfill methane (CH_4) emissions is critical to maintain the increasing global warming temperature below 1.5 °C. The Global Methane Pledge alone—aiming to mitigate worldwide methane emissions by at least 30% by 2030—could reduce global warming temperature by ~0.2 °C by the year 2050 [45]. The decision to build a strategy for methane emission depends on operational changes in landfills and plausible amendments in existing waste management systems. Mitigation of landfill methane has been performed using two distinct approaches. The first utilizes landfill methane for energy generation through burning and heat production, whereas the second seeks to reduce emissions through biological actions [43]. Landfill gas collection systems are built in most sanitary landfills; however, a small quantity of methane escapes as fugitive emissions [52]. Such practices are economical for large landfills; however, for older and smaller landfills, this method underutilizes the gas collection system [17]. The collected landfill gas is controlled and treated to decrease the plausible hazards. Combustion and flaring are the common and conventional methods of treating landfill gas. The combustion technologies incorporate flaring, incineration, boilers, and internal combustion engines that thermally destroy the landfill gas and diminish the possible global warming potential as methane and other GHG gases are oxidized [53]. Landfill gas forms a highly combustible mixture with ambient air. So, the combustion of landfill gas is recommended when the landfill gas contains more than 20% methane by volume [17]. Although combustion and thermal treatment of landfill gas is feasible, it is uneconomical as its incorporation involves considerable monetary investment and skilled supervision.

The biological oxidation of landfill methane could be a sustainable alternative to thermal treatment methods. Biofiltration and bio-cover implantation over landfill cells are the most frequently used technologies for methane oxidation [54,55]. The biofilter is a three-phased bioreactor consisting of a solid layer, biofilm, liquid layer, and gas phase in the form of gaseous pollutants [56]. The biofilm component follows the attached growth process principles that promote contact between microorganisms and methane to immobilize and oxidize methane, as explained in Figure 2. The biofilters can be open or closed systems, organized within the landfill covers with equipped ventilation layers. With the upward flow of landfill gas, oxygen diffuses from ambient air to the ventilation layer, which carries the methane oxidation aerobic action [54]. The circulation of gases, methane oxidation and overall performance of the biofiltration are assessed by operational parameters such as inlet load (IL), elimination capacity (EC), and conversion efficiency (η) [57]. Optimizing operational parameters in a closed biofiltration system is relatively convenient, resulting in more than 90% (η) of methane

oxidation efficiency [58]. In a recent study, biofilters were found effective in removing ($\eta > 85\%$) volatile organic compounds and inorganic substances along with methane from landfill gas [59]. Recently, the worldwide application of bio-covers in place of soil covers has also gathered attention for methane removal and, in turn, aims to reduce greenhouse potential [55,60–63]. In general, bio-covers consist of two components, including amended compost and gas distribution layers for optimization of effective methanotrophic activity and consumption of methane as food energy source by methanotrophs [63]. The distribution layer, made up of gravel, reinforces the flow of polluted gas, and the top bio-cover performs microbial activities as shown in Figure 2. Based on previously available information, various attempts have been made to reduce the methane emission through bio-cover technology [61]. The attempts for biofilters and bio-cover technologies for the inundation of GHG emissions are consolidated in Table 2. Methane oxidation through biochemical reactions, chlorination, atmospheric hydroxyl [OH] and methanotrophs in biological ecosystems significantly reduces the methane lifetime in the air to 9.1 ± 0.9 years [63].

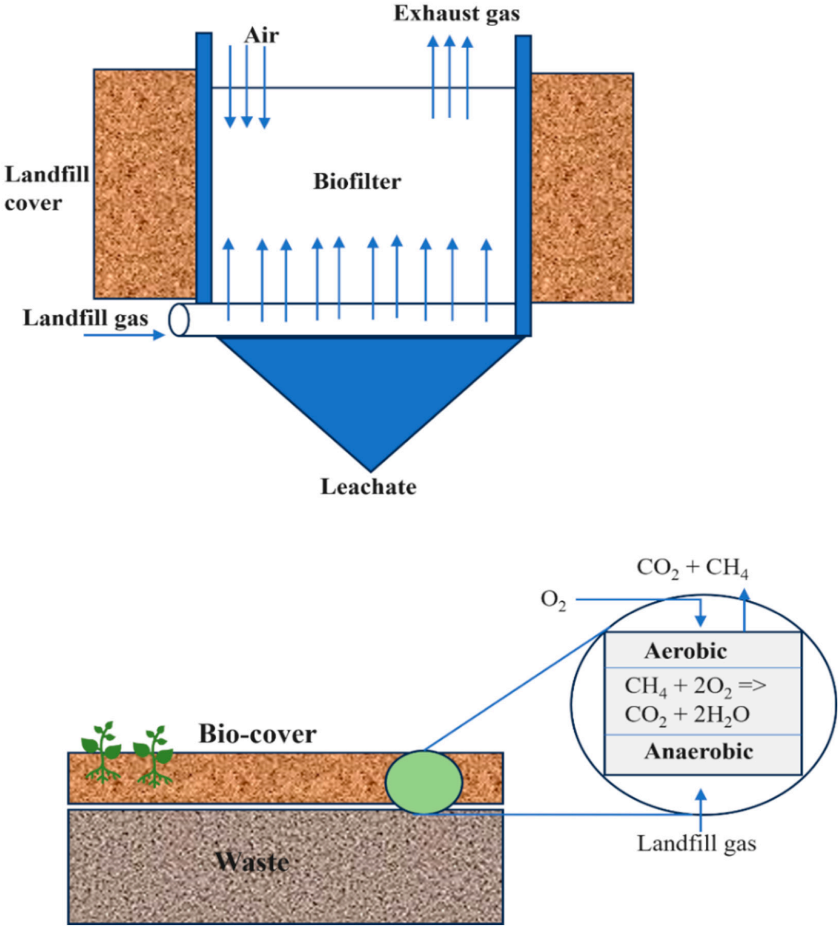


Figure 2. Biological (biofilters and bio-cover) treatment methods for landfill gas.

A recent long-term study investigating the performance of bio-covers in full-scale landfills reported that landfill-mined waste, natural mineral soil and sewage sludge compost in a 3:1:1 proportion reported variable methane oxidation across the landfill and stabilization of oxidation after stabilization of bio-covers in 5–6 years after placement [64]. The study recommended the full-scale utilization of bio-cover technology to counter climate change actions as it aligns with the United Nations Sustainable Development Goal (SDG) 13 which urges to '*Take Urgent Action to Combat Climate Change and its Impacts*'. Moreover, using landfill fine fractions as bio-cover additives follows basic CE principles and has significant potential for reducing methane emissions. In perspectives of CE implementation

and climate change mitigation and adaptation scenarios, stringent policies for efficient application of such solutions need to be enforced by governments. The regulations must be framed to mandate waste diversion targets from landfills, energy recovery plans, and linking carbon-credit incentive schemes for bioenergy utilization for smooth transition to augment circularity in landfilling sector.

Table 2. Summary of studies (both lab-scale and field-scale) for methane oxidation through biological methods, including biofiltration and bio-cover applications.

Biofiltration							
Laboratory Setup or Site Specifications	**Packed Bed Materials**	**Nutrients/Inoculum Used**	**Oxygen: Methane Ratio(s)**	**Inlet Methane Load (IL) ($CH_4/m^3/d$)**	**Empty-Bed Residence Time (EBRT, min)**	**Methane Conversion Efficiency (η, %)**	**Reference**
Biofilter, volume 18	Stone material (void fraction 0.43)	N, P as nutrient source, activated sludge as inoculum	210:1, 123:1, 161:1, 105:1, 70:1, 52:1, 28:1, 21:1, 16:1	162, 275, 210, 323, 485, 647, 1212, 1617, 2102 (respectively)	1 to 7	87% (at IL of 162) to 53% (at IL of 2102)	[58]
Work volume 7.85 L (height = 1.2 m, Diameter = 0.1 m)	Composted leaves (60%) and inorganic materials (40%)	Activated sludge and compost	6.7:1 to 59.8:1	78 to 3556	7.4 to 42.8	90–95% (from IL 77 to 320)	[65]
Continuous stirred tank reactor (~10 L)	Activated sludge, plastic bio-balls, gravels	Nitrate salts	20:1	9 to 47	200 to 998	99% at IL = 9 and 60% at IL = 47%	[66]
Inner reactors (6283 cm^3)	Bio-complex textile with perlite/tobermolite, sand and Hyuga pumice	Nitrate salts, earthworm cast (inoculum)	3:1	100	571	90%	[67]
Cylindrical columns (height = 0.45 m; inner diameter = 0.08 m)	Impregnated Kaldnes rings,	Centrate wastewater from digested sludge	4.3:1	2591	17.5	<20%	[68]
Column bioreactor (Inner diameter = 0.14 m; height = 0.88 m)	Lava rock (3–20 mm dia), wood biochar and compost	Compost	2.5:1	867	83	100% (from 1:1, 3:1 mix)	[69]
Upflow reactors Work volume: 0.018 m^3 (1 m height and 0.15 m diameter)	Inorganic packing material	Leachate from active biofilter	2.75:1	10 to 30	4.5	85 to 90%	[59]
Bio-Cover Application							
Experimental Set Up or Landfill Site	**Landfill Cover Material (s)**	**Type of Experiment**	**Methane Oxidation Rate ($gCH_4/m^2/d$)**	**Methane Loading ($gCH_4/m^2/d$)**	**Methane Oxidation Efficiency (%)**	**Methane Flux at Output ($gCH_4/m^2/h$)**	**Reference**
Column set up (Height = 1.07 m and Diameter = 0.19 m)	Landfill cover soil	Column experiment	NA	35.3–84.7	74–94%	2.4–3.53	[70]
Column (Height = 70 cm and Diameter = 9 cm), Volume = 4453 cm^3	Biochar, soil and biochar amended soil	Column experiment	6.84–24.3	25.4–56.8	24–48%	~21.5	[71]
Columns (1 m height, 18.4 cm inner diameter)	Mixed soil-biochar	Column experiment	1.65–4.00	~80	60–90%	9–36.3	[72]
Batch = 250 mL Column (height = 78 cm, diameter = 20 cm)	Soil + sulfate, Soil + Nitrate, Soil + Sulfate + Hematite, soil	Batch and column experiment	NA	179.4	85%	26.7–62.3	[73]
Glass bottles (120 mL) batches	2 g compost bio-cover material	Batch experiment	175–180 μmol/g/d	95.9 μmol/g/d	80–95%	NA	[74]
Engineered column (Height = 90 cm, diameter = 15 cm)	Biosolids from wastewater treatment plant	Column experiment	188–237	60.35–90.12	40–65%	6.98–19.53	[75]

3. Circular Economy and Climate Change: Roles of Technologies, Proposed Solutions and Emerging Trends

Energy accessibility has changed humanity and consumerism over the last few decades. The demanding energy sector is the largest contributor to GHG emissions and instigates climate change, which disrupts the energy networks, stresses energy infrastructure, and imposes health safety risks to people [76]. Energy generation from conventional sources is non-sustainable due to resource limitations, environmental hazards, and draining supplies. Currently, 80% of the energy demand is fulfilled by fossil fuels, which extensively exploits the rapidly decreasing fossil fuel reserves with detrimental environmental events [77]. Even though the recent global energy consumption rate slowed down (2.1% in 2022), it remained higher than its growth rate of 1.4% in the previous decade (2010–2019) [77]. Recent global energy demand forecasting showed an accelerating trend with annual consumption to attain ca. 778 EJ by 2035, which imposes an additional load on conventional resources [78].

Various studies underscore the critical role of the waste sector in climate change mitigation. Zhang et al. [79] and Sun et al. [48] reported that incorporating recycling into landfill management significantly lowers carbon emissions. Waste-to-energy (WtE) incineration, combined with material recovery, can further reduce emissions while generating electricity in less time [16,80]. Among recent technologies, WtE technology is vital for curbing climate change impacts as they address GHG emissions at waste management and energy production stages [81]. First, it substantially decreases methane discharges by switching organic and burnable waste away from dump sites, where anaerobic degradation generates biomethane which is utilized as energy. Similarly combustible fractions are treated thermally in incinerators or gasifiers to produce synthetic gases of fuels [82]. Secondly, such systems also produce electricity or heat, which replaces the need for fossil fuel-based energy systems, avoiding carbon emissions. Moreover, WtE adopts material retrieval and CE principles by facilitating the recovery of nutrients, metals, and usable residues, thereby decreasing GHG emissions linked with exploitation of virgin raw material [83]. Successful implementation of such a paradigm shift in existing solutions and continuous advancements is vital for reducing climate change impact and promoting CE practices.

3.1. Waste-to-Hydrogen Technologies: Potential and Challenges

Hydrogen is widely recognized as a clean and versatile energy carrier, offering a promising route to decarbonize industrial processes, transport, and power generation. Integrating waste-to-hydrogen (W2H) technologies within a CE framework not only provides an innovative energy recovery pathway but also maximizes resource efficiency by valorizing municipal, industrial, and agricultural residues [84]. Waste streams, including organic fractions, plastics, and sludge, contain significant energy potential that can be converted into hydrogen through thermochemical processes (e.g., gasification, pyrolysis, and plasma-assisted conversion) and biological methods (e.g., dark fermentation and AD) [85].

The potential benefits of W2H technologies are multifold: First, they reduce the reliance on fossil fuels, mitigating greenhouse gas emissions and air pollution. Second, by recovering energy from waste, they create economic value from materials that would otherwise contribute to landfills or uncontrolled emissions. Third, W2H systems can be modular and scalable, enabling deployment at local, regional, and industrial scales while supporting decentralized energy production. In addition, integrating hydrogen production with existing waste management infrastructures strengthens the CE by closing material and energy loops and promoting sustainable industrial symbiosis (IS) [86]. IS could considerably enhance the effectiveness and economic viability of W2H systems by allowing multi-sectoral utilization of solid waste, hydrogen and industrial by-products [87]. In IS systems, biowaste, refuse-derived fuel (RDF), plastic waste, and industrial organic

waste produced from one industry or municipality could be raw materials for hydrogen and biogas yield by thermochemical and biomethanation processes [88]. Moreover, surplus heat, steam, and carbon dioxide produced while thermal or biological processes may be channelized by nearby industrial units, thus enhancing total energy efficacy and decreasing operating budgets. Despite its promise, several challenges must be addressed to enable widespread adoption. High capital costs, complex reactor designs, and energy-intensive pre-treatment of waste remain significant barriers. Moreover, the heterogeneity of waste streams can affect hydrogen yield and process efficiency, requiring advanced sorting, feedstock conditioning, and process optimization [89]. Lifecycle environmental impacts, including potential emissions from energy inputs and by-products, must also be carefully evaluated to ensure genuine sustainability gains [90]. Finally, policy, regulatory frameworks, and market mechanisms for green hydrogen remain underdeveloped in many regions, posing additional hurdles for industrial-scale implementation.

Future research should focus on optimizing hybrid W2H systems, combining biological and thermochemical routes to improve hydrogen yield, energy efficiency, and environmental performance. Table 3 summarizes thermochemical routes of W2H production. Pilot-scale demonstrations, techno-economic analyses, and lifecycle assessments are critical to validate the scalability, feasibility, and circularity benefits of these technologies. By addressing technical, economic, and policy challenges, waste-to-hydrogen systems can play a transformative role in achieving a low-carbon, resource-efficient, and sustainable energy future, as depicted in Figure 3.

Table 3. Thermochemical treatment methods for energy recovery from waste materials.

Thermochemical Treatment	Feedstock Waste Material	Temperature Range (°C)	Energy Yield	Reference
Gasification	Wood chips or pallets	700–800	17.5% H_2, 19% CO, 16.9% H_2, 20% CO	[91]
	MSW	500–900	Syngas (84%)	[92]
	MSW	850	14% of total syngas	[93]
	Discarded plastic waste	594–649	~6.5% H_2	[94]
	Solid residual fuel and lignite	750–850	56.34% of H_2	[95]
	Softwood pellets	700–800	36.5% of H_2	[96]
Pyrolysis	Waste plastics	400–500	Gasoline, Diesel	[97]
	Low-density polymer	450–600	Gasoline	[98]
	Plastic waste	1000	Syngas	[99]
	Frying oil and plastics	550	Biodiesel	[100]

3.2. Waste-to-Energy Power Plants: Multi-Objective Optimization

Waste-to-energy power plants are pivotal in transforming municipal and industrial solid wastes into sustainable energy, offering a dual benefit: reduction of landfill volumes and generation of electricity or heat [101]. Modern WtE systems employ multi-objective optimization strategies, balancing energy recovery, greenhouse gas mitigation, and operational efficiency [102]. By integrating innovative technologies such as leachate recirculation, methane generation can be enhanced while minimizing environmental impacts from untreated leachate discharge.

Leachate recirculation accelerates the degradation of organic waste, improves biogas yield, and maintains optimal moisture content for microbial activity [30,43]. This approach not only increases methane capture but also reduces post-treatment costs and the long-term environmental burden of landfills [103]. Moreover, combining heat recovery from incineration or AD with leachate optimization supports integrated energy management,

maximizing both electricity and thermal outputs [104]. The advantages of WtE systems extend beyond energy generation [105]. They reduce reliance on fossil fuels, lower GHG emissions, and contribute to CE goals by closing the loop on waste material recovery. Abdel-Shafy and Mansour [106], de la Barrera and Hooda [107], and Turner et al. [108] also demonstrated GHG and carbon emissions through sustained recycling associated with different processes. They also advocated recycling source-segregated waste material, excluding soil, paint and plasterboard. Recycling is becoming a powerful tool in the pathway to sustainable development. Nevertheless, implementing recycling measures for regions with poor waste segregation is challenging. Also, the quality of recycled material and the continuation of energy efficiency are areas of concern. Thus, amendments in recycling measures may also be required to maintain energy efficiency and the process's sustainability.

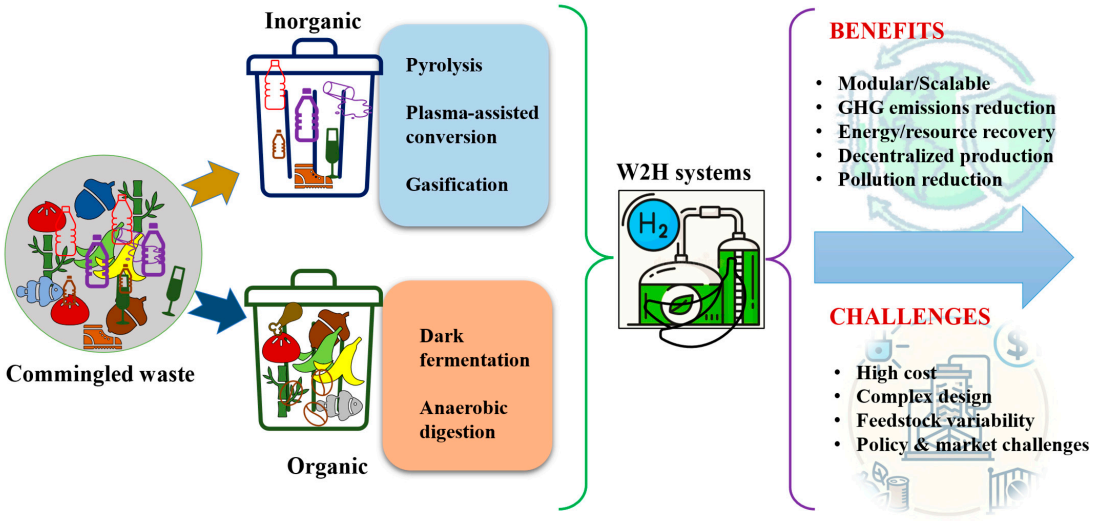


Figure 3. Waste-to-hydrogen systems: pathways, challenges, and benefits in the CE.

However, challenges remain, including high capital and operational costs, heterogeneous waste composition, and the need for advanced monitoring systems to prevent air and water pollution. Multi-objective modeling, lifecycle assessment, and techno-economic evaluation are essential to ensure sustainable deployment. A short tabular review summary of various feeds, technology, associated methodology, major outcomes and bottlenecks related to waste-to-energy technologies is represented in Table 4. Future research should focus on enhancing system integration, exploring hybrid approaches combining AD, gasification, and thermal incineration, and developing predictive models for optimal leachate recirculation [103]. In this regard, Table 5, emphasizing comparative evaluation of advanced WtE and resource valorization technologies in municipal and industrial sectors, could provide recommendations for appropriate measures to be taken in the future.

Table 4. Comparative assessment of diverse feedstocks, valorization technologies, associated methodologies, cardinal outcomes and bottlenecks related to various waste-to-energy technologies.

Feedstock/Waste	Technology	Methodology	Outcomes & Challenges	References
MSW	Mechanical Biological Treatment (MBT) Incineration	Comparison of environmental, economic, and energy recovery performance	MBT: High energy recovery (38.5%), air pollution reduction, weak economic performance, requirement of economic support policy Incineration: 20.5% energy recovery, higher lifecycle impact	[109]
Food, yard, plastic, paper, wood, textile wastes	Gasification Incineration AD Bio-landfill Composting	Comparison of recycling ability, energy production, and environmental impact quantification	Recycling: paper, wood, plastic AD: food and yard waste Incineration: Textile AD and gasification better in environmental performance, and composting the least	[110]

Table 4. *Cont.*

Feedstock/Waste	Technology	Methodology	Outcomes & Challenges	References
Food waste, Wood chips	AD + Gasification	Comparison of energy performance with the single and integrated AD & gasification systems	Synergistic energy recovery (methane yield of AD of FW;0.52 L CH_4/g VS/d, high calory producer gas), improved system efficiency, waste minimization	[111]
MSW	(1) Material recycling (2) Composting (3) Thermal conversion	(i) Recycling paper, glass, plastic, and metals and landfilling the remaining waste (ii) Recycling all the recyclables and composting organic wastes (iii) Incineration for energy recovery	Material recycling and thermal conversion reduces climate change impact Saved GHG emissions of 275,449 tCO_2 eq/yr, 287,868 tCO_2 eq/yr, and 652,626 tCO_2 eq/yr for (1), (2), and (3)	[112]

Table 5. Comparative evaluation of advanced W-t-E and resource valorization technologies in municipal and industrial sectors.

Technology	Feedstock	Operational Strategy	Energy Output	Environmental & Process Benefits	CE Leverage	Reference
Bioreactor landfilling	MSW, paper mill effluent	Co-digestion, leachate monitoring	Biogas (Methane)	Enhanced methane capture, significant leachate quality (97% BOD removal)	Landfill diversion, waste minimization, pollution abatement, resource recovery	[25]
Anaerobic co-landfilling	MSW, sugar mill press mud	Biomethane production, leachate characterization, leachate recirculation	Biomethane	Enhanced methane capture, waste degradation, improved leachate quality	Landfill diversion, resource and energy recovery, waste valorization	[37]
Bioreactor landfilling	MSW, alkaline paper mill sludge	Co-disposal of lime sludge with MSW, leachate and biomethane analysis	Biomethane	Reduction in leachate organic strength (~77%), enhanced biomethane production (8.315 L)	Pollution abatement, energy recovery	[113]
Gasification	MSW, plastic waste, tires	High-temperature gasification (steam-catalytic/air)	H_2, Syngas	Enhanced H_2 productivity (300 g H_2/kg feedstock), reduction in landfill loads	Conversion of diverse waste streams into hydrogen fuel, supports renewable energy market	[114]
Steam co-gasification	MSW, paper mill sludge	Production of syngas, fuel conversion, energy recovery	H_2, Syngas	81% H_2 production, 2.82 m^3/kg syngas yield, CO_2 emission reduction	Energy recovery, capture CO_2 emission, waste valorization	[115]
Pyrolysis/Co-pyrolysis	Paper mill sludge, textile dye sludge	Independent pyrolysis and co-pyrolysis of feedstocks with duck weed and waste tire	Pyrolysis gas, oil, char	Degradation of harmful organic matter in sludge, reduced solid residue yield of PMS, effective reduction in activation energy, improved yield of liquid and gas products	Multiple-waste valorization, landfill diversion; supports hydrogen economy	[116]
AD	MSW (Chennai Kodungaiyur and Perungudi landfills)	Evaluation using energy-economic-environmental (3E nexus) analysis	Biogas, electricity	Net emission reduction (136.36 tCO_2/day), enhanced digestate recovery	Energy recovery, economic return, climate benefits	[117]

By addressing these challenges, WtE power plants can evolve into efficient, scalable, and environmentally sustainable solutions for urban waste management. The multi-objective optimization strategies practiced in WtE plants and their associated benefits and cons are presented in Figure 4.

3.3. MSW to Energy: Characteristics, Management Strategies, and Role in Circular Economy

Municipal solid waste (MSW) represents a growing challenge due to rapid urbanization and increasing consumption patterns [118]. Transforming MSW into energy offers a sustainable route to reduce environmental burdens while producing electricity, heat, or fuel. MSW-to-energy (MSW-to-E) technologies encompass incineration, gasification, pyrolysis, and AD, each with unique characteristics, efficiency levels, and environmental implications [119]. Understanding waste composition—organic fraction, plastics, paper, and metals—is essential for selecting appropriate treatment strategies and optimizing en-

ergy recovery [120]. Effective management strategies for MSW-to-E systems include source segregation, pre-treatment, material recovery, and integrated energy conversion [121]. Segregation ensures high-quality feedstock, reduces emissions, and increases energy yield. Pre-treatment, such as shredding, drying, or palettization, enhances process efficiency, while material recovery enables the separation of recyclables, aligning with CE principles [122]. The integration of hybrid technologies, such as combining AD with thermal gasification, can further improve energy output and reduce residual waste.

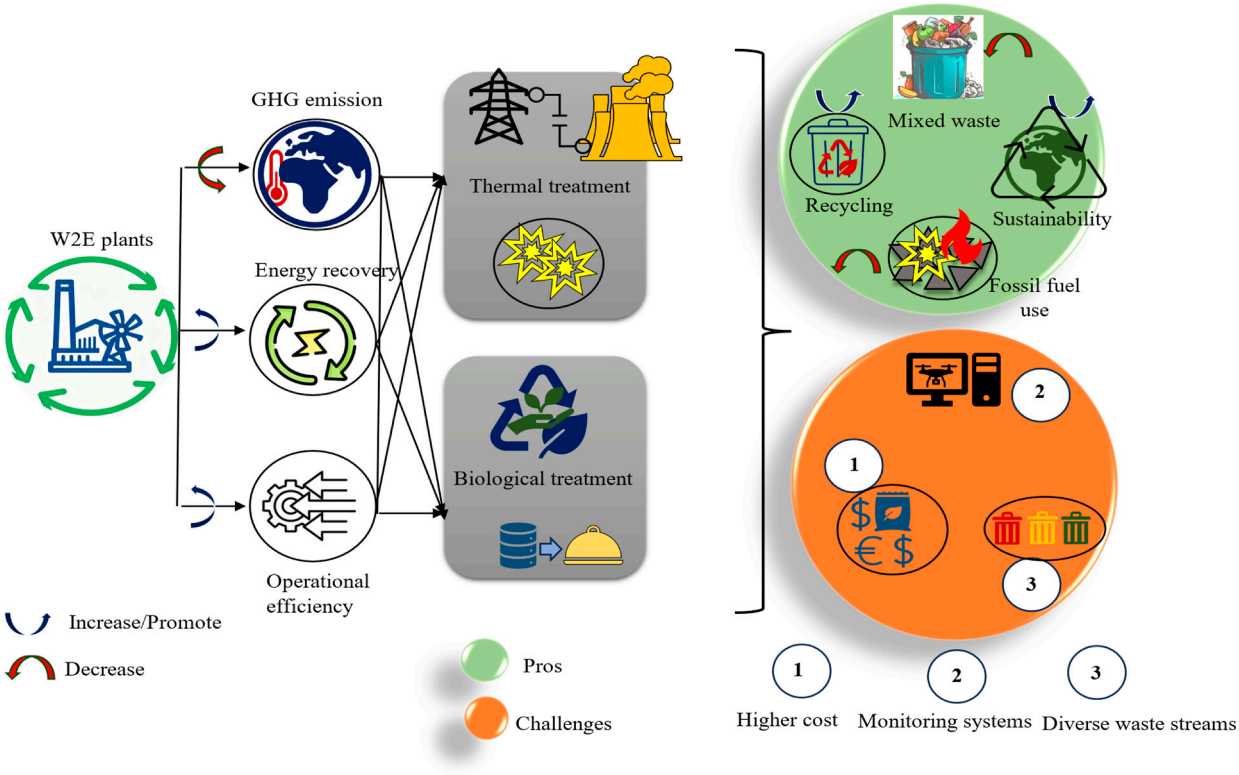


Figure 4. Multi-objective optimization strategies employed in WtE plants and its associated pros and cons.

The role of MSW-to-E technology within the CE extends beyond energy recovery. By diverting waste from landfills, MSW-to-E technology reduces greenhouse gas emissions, mitigates soil and water contamination, and enables resource valorization. Economic benefits include energy cost offset, creation of green jobs, and promotion of sustainable urban development. Among WtE technologies, AD is considered an economically viable biological treatment for high-moisture-containing wastes, with described levelized cost of energy (LCOE) varying from about 68 to 254 USD/MWh reliant on feedstock proportion, plant size, and biogas upgradation requirements [123]. However, thermochemical technologies, including gasification and W2H technologies, mostly comprise significantly higher capital and operational investments (CAPEX and OPEX) owing to feedstock pre-treatment, syngas production, hydrogen purification, and novel reactor requirements. As per recent techno-economic assessments, hydrogen produced through thermochemical conversion of waste entails levelized cost of energy (LCOE) ranging between 1.4 and 5.2 USD/kg of H_2 under optimized operations; nevertheless, the same product varies between 8 and 13 USD/kg H_2 for carbon capture solutions associated with the plasma gasification method because of higher energy demand and CAPEX [124]. Therefore, techno-economic feasibility analysis is imperative prior to adopting CE and climate mitigation strategies at macro levels. Challenges include high capital costs, heterogeneous waste streams, potential emis-

sions, and policy barriers [125]. These can be addressed through lifecycle assessments, techno-economic optimization, and regulatory incentives.

Future perspectives highlight the need for smart integration of MSW-to-E systems at city and regional levels, supported by digital monitoring, predictive maintenance, and stakeholder engagement. Such approaches ensure that MSW-to-E systems contribute effectively to climate change mitigation, energy security, and the realization of CE goals. The implications of MSW-to-energy technologies are also summarized in Table 6, in the context of GHG mitigation strategies performed at regional scales, and appropriate technologies are recommended. Considering the pivotal role of the MSW-to-E technology policy oriented towards its implementation, it should be tailored based on regional MSW specifications, lifecycle GHG reduction potential, infrastructure development budget and techno-economic assessments rather than implementing a universal WtE method.

Table 6. Municipal solid waste management and GHG mitigation strategies: regional approaches and technologies.

Country/Region	Approach/Strategy	Technologies Used	GHG Emission Reduction Outcome	Reference
Shanghai, China	Investigation of GHG emission patterns from 2016 to 2021	Forced source separation Resource recycling and AD of wet waste	Reduction in GHG emission intensity from 0.29 to 0.24 tCO_2 eq/t MSW.	[126]
Yangtze River Delta	Evaluation of mitigation potential for GHG emission (2025, 2030)	Source separation and technical measures (incineration, advanced disposal systems)	Net emission decreased after peaking at 16.34 Mt CO_2 eq in 2021 due to incineration plants; Reduced emission intensities (0.19 tCO_2 eq/t MSW) due to advanced disposal systems.	[127]
Surabya	Implementation of national policy & strategy for MSW Assessment of GHG emission transition through LCA before and after the implementation	Waste-to-energy plant Recycling RDF production	Reduced emissions from 1,004,951.5 tCO_2 eq/to 430,839.6 tCO_2 eq from waste-to-energy plants; Further reduction of 22% from recycling; RDF: 45.2% emission reduction.	[128]
Palestine	Electricity generation from waste-to-energy plants	Municipal landfills	20.5% reduction in GHG emissions (69,960 tCO_2 eq/yr).	[129]
Iran	Electricity generation potential from MSW using integrated solid waste management system	AD, incineration, pyrolysis–gasification	Reduction of 3561–4844 $\times 10^3$ tCO_2 eq (~0.5% of total GHG emission).	[130]
Croatia	Energy recovery from MSW	Landfill, RDF, incineration, MBT	Reduction of 1 million tons of CO_2 in 2020 (2.7%).	[131]
Shanghai, China (2005–2015)	IPCC recommendation and bottom-up method, shifting of waste disposal method	Incineration, landfill composting, waste source sorting	Decline of GHG emission of MSW management system to 0.354 kg CO_2 eq/kg MSW in 2015 from 0.363 kg in 2012; GHG emission intensity of incineration (0.147–0.177 kg CO_2 eq/kg MSW); 54% reduction from source sorting and incineration dominated disposal methods by 2030.	[132]

3.4. Recent Advances and Emerging Trends in Circular Waste Management

The field of circular waste management is rapidly evolving, with technological innovations and policy interventions shaping sustainable practices worldwide [133]. Recent developments include waste-to-hydrogen technologies, plasma-assisted waste valorization, and hybrid anaerobic–thermal conversion systems, which offer higher energy recovery, lower emissions, and enhanced resource efficiency [134]. Integration of digital technologies, such as AI-driven waste sorting, real-time monitoring of landfill gas emissions, and predictive maintenance of waste-to-energy plants, is transforming operational efficiency and scalability [135]. Policy and regulatory frameworks are also evolving to incentivize circularity. Examples include carbon credit mechanisms for waste-to-energy projects, subsidies for bioenergy production, and extended producer responsibility (EPR) programs for e-waste and plastics [136]. Innovative business models are emerging, such as IS, where waste streams from one facility become input for another, closing material loops at the regional scale. As a business model, IS facilitates collaborative resource sharing among solid waste streams, surplus heat, wastewater, and industrial biproducts from a cluster of

industries on pay-basis and cherish benefits of energy or products from treatment units. Moreover, IS establishes connected industrial links which upgrade resource competence, decrease waste disposal, raw material utilization, and improve affordability via shared infrastructure and diminished operating costs.

Innovative circular economy (CE) business models such as industrial symbiosis (IS) promote collaborative resource sharing in which waste streams, excess heat, water, or industrial by-products from one facility are utilized as raw materials or energy inputs for another industrial process. Unlike conventional linear production systems, IS creates interconnected industrial networks that improve resource efficiency, reduce waste disposal and virgin material consumption, and enhance economic competitiveness through shared infrastructure and reduced operational costs. Such regionally integrated CE models can additionally support climate change mitigation by lowering lifecycle greenhouse gas emissions and enabling low-carbon industrial production systems.

Furthermore, social innovations in waste management are gaining attention. Community-based recycling programs, informal sector integration, participation of social communities as major stakeholders and CE awareness campaigns ensure that sustainability efforts are equitable, inclusive, and resilient. The consolidated picture of recent technological and social innovations in circular waste management is presented in Figure 5.

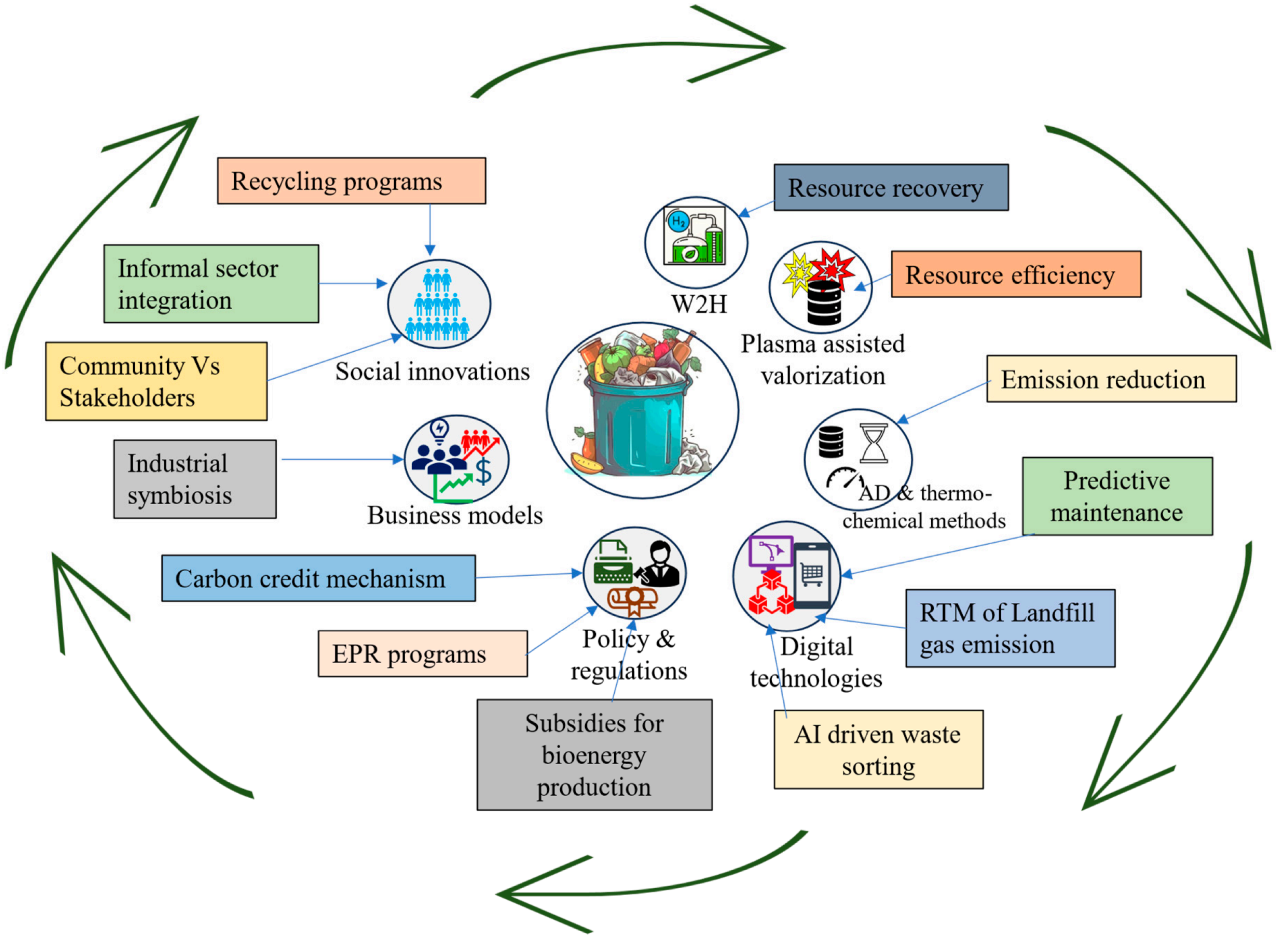


Figure 5. Recent technological and social innovations in circular waste management.

These emerging trends highlight the dynamic potential and expanding scope of circular waste management, offering actionable pathways for policymakers, industry stakeholders, and researchers to achieve climate goals, resource efficiency, and sustainable urban development.

3.5. A Three-Stage Solution in the Circular Economy

The CE is increasingly being recognized as a strategic tool to combat global warming while promoting sustainable development at the local, regional, and national level [78]. Unlike the conventional linear economic model, which relies on a take–make–dispose approach, the CE emphasizes the efficient use of resources, closing material loops, and recovering energy from waste. Its implementation can catalyze long-term economic growth while mitigating climate change impacts [137]. CE strategies can be applied at multiple scales—micro, meso, and macro—depending on the scope and stakeholders involved (Figure 6). At the micro level, individual firms or households can adopt practices such as recycling, reusing, and repairing materials to reduce waste and conserve resources. At the meso level, IS and collaborative networks enable organizations to exchange waste or by-products, enhancing efficiency and resource utilization. IS differs from another significant waste management system, i.e., integrated solid waste management (ISWM). ISWM particularly focuses on systematic municipal and industrial waste management with organized segregation, collection, transportation, recycling, and waste-specific treatment, including biological and thermal, and environmentally sound disposal methods. The prime aim of ISWM is to significantly decrease environmental effects and augment material and energy recovery. However, IS adopts cooperative sharing of waste materials, energy, water, and industrial biproducts among various industries, where the waste from one unit becomes usable for another. Conclusively, ISWM primarily targets systematic waste processing, while IS promotes collaborative resource utilization for closing the loop of material and energy. At the macro level, national policies, regional collaborations, and international agreements facilitate large-scale CE adoption through climate cooperation policies, carbon credit mechanisms, and integrated waste management strategies [137,138].

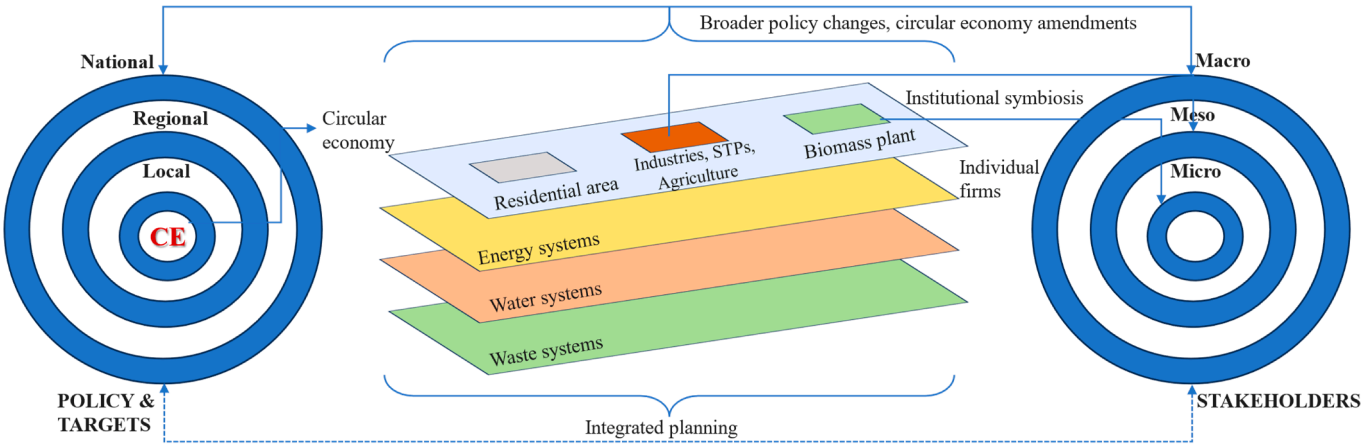


Figure 6. Plausible framework for an integrated CE approach confining authorities, policies, and actions to be taken at local, regional and national levels.

The CE streams are bifurcated into broad areas encompassing biological and technological flows. Since biological flows target the reuse of energy potential from organic wastes through bioprocessing techniques, it is imperative to understand the potential for producing energy from waste material before implementation. Nevertheless, these prerequisites before opting for biological solutions impose fundamental challenges for building up circularity within the current urban practices. The technical flows also deal with the smooth running of recovery, reuse, remanufacturing and recycling units. While these flows offer clear environmental advantages, it is equally important to recognize the systemic complexities and potential trade-offs involved in their implementation. Advanced recycling and waste-to-energy processes often require higher energy inputs, sophisticated

infrastructure and, in some cases, additional natural resources. Without proper planning, these requirements could offset part of the environmental gains. Recent lifecycle assessments indicate, however, that despite higher upfront energy demands, CE systems achieve a net reduction in greenhouse gas emissions and resource depletion compared with landfill-based waste management [82,139]. This underscores the need for a holistic systems perspective to ensure that the transition to circularity maximizes benefits without creating hidden environmental costs. The implementation of circularity at different scales has the potential to generate socio-economic and environmental benefits at the urban level. Thus, identifying flows is crucial in defining the overall efficiency of a CE. In the domain of waste management in urban areas, a CE aims to include all possible flows concerning material and energy to address the environmental and social problems in various sectors (Figure 6). Notably, the individual sectors of urban communities could be classified as micro, meso and macro based on socio-economic impacts, inventory requirements and policy perspectives. Considering different flows of CE, energy, water and waste recycling systems can be technically associated with various sectors depending on their requirements and impacts. CE initiatives with improved technical and biological flows can be developed through the efficient involvement of stakeholders, including government, policymakers, businessmen, and consumers. Such systematic amendments are required for the transition from linearity to circularity, which demands exertions at different levels.

Published studies have highlighted that the identification of material and energy flow, their integration to support CE, and the determination of institutional governance for overcoming the barriers of sustainable development are areas for addressing the transition to urban sustainability [137,140–142]. Identification of flows involves assessment of technical and biological areas. Technical flows incorporate activities essential to maintain material flow, such as reuse, recycling, recovery, repair, and refurbishment. Application of the 9Rs framework for the transition from linear to CE is recommended for better results [143]. However, biological flows include directly using organic material via bioprocessing, such as composting and AD [144]. Since understanding the reusability of each material category is very challenging for establishing a CE in the existing system, integration of all possible flows (material and energy) is recommended to change the perception of waste as a 'problem' [145].

Although climate change mitigation must adopt global solutions, the involvement of stakeholders from individual to international level (business, academia, consumers, industries and government) is required for such initiatives [140]. Thus, promoting circularity through vigilant governance actions, aiming at integrating individual scales and focusing on decarbonization and climate change mitigation, is needed nowadays [143]. Moreover, target setting from local to national levels to foster the establishment of CE measures is recommended to improve efficiency [137]. The suggested three-staged CE framework grants an organized pathway for rendering circularity concepts into plausible urban interventions. Together, aforementioned recommendations warrant that CE application needs to be systemic rather than divided. Based on this multi-staged solution, it is also imperative to gauge how such integrated CE interventions participate in broadening sustainability solutions, specifically the attainment of the UN-SDGs. The effects of CE strategies are non-exhaustive to resource management alone but even expand to climate action, economic resilience, public health, and social equity. Conversely, the scope of SDG implementation and the associated challenges vary due to various factors. Therefore, the following section assesses the benefits and challenges of CE strategies in the context of SDG attainment.

A suggestive case study regarding implications of the proposed CE framework can be observed at the macro level where AI- and IoT-enabled MSW management systems are integrated with decentralized waste segregation and biomethanation plants. Placement

of smart bins associated with IoT devices and AI-aided waste identification systems produce temporal data on MSW composition, methane hotspots, and contamination rates. A pilot plant in Mumbai, India, exhibited a nearly 20–35% decrease in fuel requirements by enabling AI-based and IoT sensor-optimized pathways for waste identification [82]. Moreover, surfeit instances and MSW collection inadequacies were decreased extensively through AI-based modeling and GIS-driven logistics routes. Furthermore, at the meso level, integration of material recovery facilities and biological treatment units optimize bioenergy production, waste hauling and recycling schedules. Based on seasonal variation, the Indian biowaste fetched biomethane potential ranging from 175 to 286 $NLCH_4$ $kgVS^{-1}$ for a decentralized AD unit [146]. Operational and emission databases could eventually inform macro-level governance systems, incorporating renewable energy solutions, carbon crediting, and methane mitigation plans. For example, AI-enabled regional waste management systems could advocate evidence-based policy decisions related to biogas upgradation infrastructure and national climate change mitigation goals. Therefore, concurrent data produced at the micro level prominently contribute to macro-level CE policymaking.

4. Contribution of Circular Economy Towards SDGs Attainment: Benefits and Challenges

The CE is a model of production and consumption that emphasizes sharing, recycling, refurbishing, and reusing materials and products as much as possible [147]. It aims to address global challenges such as unprecedented waste generation, biodiversity loss, climate change, and environmental pollution by implementing three fundamental principles: regeneration of natural systems, redesign of waste treatment systems, and prioritization of recyclable and reusable materials [147,148]. The CE framework is facilitated in "9R" hierarchical order which prioritizes refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover methods as per their treatment potential [149]. The 3Rs, including refuse, reduce, and reuse, are higher-order strategies which grant environmental and climate change mitigation advantages through solid waste reduction and decreased pristine material utilization. Similarly, recycling and recovery streams provide the possibility to manage residual waste and recover beneficial materials from it. Energy and material recovery from waste represents a core component of the CE, helping reduce waste, conserve natural resources, and minimize environmental impacts [148]. When implemented effectively, CE strategies influence energy consumption, material resource use, air and water quality, solid waste generation, land use, and land cover. Thermal methods, including pyrolysis, gasification, and incineration, as well as biological processes like AD and composting, have been widely applied to recover energy and valuable resources primarily from residual or non-recyclable waste fractions leftover after feasible reduction, reuse, segregation and material recovery [150].

Recently, Padmanabhan et al. [151] demonstrated that pyrolysis of waste plastic can serve as an alternative fuel, improving thermal efficiency by 4.8% and decreasing fuel consumption by ~8%. Non-recyclables waste with high energy potential can replace fossil fuels and reduce conventional energy resource consumption and greenhouse gas emissions [152]. Nevertheless, extreme dependency on thermal treatment of mixed MSW could clash with high-order CE methods targeted on waste restraining, reuse, and recycling. Hence, integration of thermal recovery technologies as corresponding downstream processes is recommended within wider CE contexts focusing on source segregation and material recirculation.

Thermal treatment methods of solid waste, including pyrolysis and gasification, have significant potential to reduce methane emissions via combined heat and power generation and biowaste utilization as renewable energy sources, which follow the pathways

of CE for sustainable development [80,153–156]. The combination of biological and thermochemical conversion of waste has further encouraged the CE approach as integrated technologies have better possibilities for decreasing adverse environmental impacts and enhancing resource efficiency [157]. It is worth mentioning that thermal plasma-assisted waste valorization processes are a recent development in thermal methods to treat various types of wastes and recover energy and valuable materials, meeting the prerequisites for being an energy alternative and possessing the potential for climate change mitigation with minimum GHG emissions [158]. However, being at the growing stage, lack of process understanding, high upfront capital cost, and electricity utilization as input are areas of concern before full-scale deployment [159]. Furthermore, co-valorization of sewage sludge and refuse-derived fuel as difficult wastes in thermal plasma is an effective and environment-friendly technology for syngas production and reduction of GHG emissions to a significant extent [160]. The inter-relation depicted in Figure 6 clarifies how CE initiatives have considerable potential to reduce GHG emission at various steps of circularity.

Biological waste treatment methods are important pillars of the CE through GHG emissions mitigation, nutrient recycling, prevention of pollutant leaching to groundwater, and spread of harmful diseases through open dumping or un-engineered landfilling [42]. Biogas generated through AD is an energy carrier, potentially feasible for storage and electricity generation [30,33,43]. The energy generation from biogas relies on the type of feed waste, plant design, temperature and digestion time. A common feedstock in Germany generates ca. 8 times more biogas than cow manure, thereby contributing to high energy potential [161]. In India, biogas energy capacity was reported to be ca. 14 MW in 2022, which is expected to increase further by five times in the coming decade [162]. Composting is another biological method that improves the ecosystem through nutrient recycling, which reduces the use of synthetic fertilizers and other material resources. MSW treatment technologies employing CE fundamentals in the perspective of different application motives and application impacts in view of social, environmental and economic aspects are reflected in Table 7.

Table 7. Summary of MSW treatment technologies following CE fundamentals in the perspective of different application motives and application impacts vis-à-vis social, environmental and economic aspects.

Type of Waste, Region or Country	Technology	Application Motive	Application Examples	Overall Impact of Technology			Reference
				Social	Environmental	Economic	
MSW (biodegradable material > 7%), Delhi, India	Landfill gas recovery technology	Energy and electricity	Landfill methane collection as feedstock	Nearby areas for energy through methane capture	GHG emission reduction, particulate capture	Potential for electricity production for 8–15 million houses (the year 2014)	[163]
Biodegradable MSW, China	Extraction well system in landfills	Energy and electricity	Biogas production for power generation (for vehicles and pipeline fuel)	Engineered disposal as an alternative to open disposal for hygienic surroundings	Potential to replace ~86% of electricity or ~26% of natural gas consumption or 90–220 kilotons of coal and reduce CO_2 reduction by 350–900 kilotons (year 2020)	Equivalent to 225 kilotons of coal for energy generation	[77]
Organic fraction of MSW, Saudi Arabia	AD and gas turbine	Energy and electricity	Cogeneration of heat and electricity from methane, use of electricity for H_2 production through electrolysis	Hydrogen and power generation as an alternative to conventional resources	Reduced carbon emission by 3.5% by using a proton exchange membrane electrolyzer	Membrane electrolyzer is 3% more efficient than alkaline electrolyzer and produces 34% more H_2 production	[145]

Table 7. *Cont.*

Type of Waste, Region or Country	Technology	Application Motive	Application Examples	Overall Impact of Technology			Reference
				Social	Environmental	Economic	
Domestic waste (paper, plastic, metal, wood, glass, food waste), Greece	AD, landfilling and biogas for combined heat and power (CHP) production	Energy and electricity	CHP from methane through full-scale AD and sanitary landfilling	Reduction in fossil fuel for electricity generation through CHP application	Reduction in GHG emission and leachate production decreased uncaptured methane	Energy production value is predicted to 16–25% higher than landfilling	[164]
MSW landfill mined waste (70% fine gravel, sand, silt, clay, stones, plastic, wood, and others), Delhi, India	Biological aging, bio-drying, sieving	Fertilizer or compost-like application	Utilization of soil like fraction of mined waste for embankment building and as compost	Mining of old waste dumps (consisted of ~60% of total excavated waste), city aesthetic improvement	Low-nutrient compost in non-agricultural applications (parks, inedible crops)	Reduced need of fresh soil, use of mined waste as backfills reduced cost	[165]
Organic fraction of MSW, Mirandela, Portugal	Solvent and microwave-assisted extraction	Fertilizer application	Liquid manure extraction	Advancing liquid fertilizer production, promoting hygienic and organized waste disposal	Reduces water and energy requirement for extraction by 53–250 and 12–18 times, respectively	Solvent extraction is less expensive than microwave extraction; alkaline extraction are 12 times higher than water-based extraction	[166]

4.1. Benefits of Circular Economy: Emission Reduction and Economic Insights

In the context of sustainability, the CE strategies have contributed significantly to environmental and economic benefits. The CE strategies enhance economic viability even in resource-constrained settings. Revenue generation from recovered materials, energy production from waste, and long-term cost savings from reduced landfill use make circular approaches financially attractive to municipalities [167]. To ensure practical adoption, particularly in developing economies or regions with limited infrastructure, cost–benefit analyses and supportive funding mechanisms such as subsidies, tax incentives, and public–private partnerships are essential. These measures help offset initial investment costs, demonstrate financial feasibility, and encourage stakeholders to transition from traditional landfill practices. Recycling not only reduces emissions and promotes resource conservation but also provides tangible economic returns, contributing directly to the achievement of SDG 7, 11, and 13 [168]. The CE strategies have demonstrated significant environmental and economic benefits across various levels viz. industrial, corporate, and macroeconomic. The Ellen MacArthur Foundation and McKinsey forecasted that CE solutions including waste material reutilization, extending product lifecycle, recycling, and material remanufacturing can potentially improve resource efficiency by ~3% by the year 2030 in Europe, saving ~€600 billion per annum and broadening financial benefits to approximately €1.8 trillion [169]. Moreover, at the industrial scale, the Kalundborg Eco-Industrial Park, Denmark, demonstrates IS, attaining ~3 million m^3 groundwater annually, ~1 million m^3 surface water, ~170,000 t gypsum, and fetching ~15 million USD per annum as direct savings [169]. Moreover, the remanufacturing CE strategies implemented in the USA reflected that remanufactured/refurbished products require only ~15% of the resources as compared to new products, which could save ~400 trillion BTU per annum energy and avoid ~28 million tons of possible pollution [170]. The policies on material circularity fetch higher energy gains; for example, aluminum recycling requires ~10% less energy than that of primary requirements, and recycling of steel waste considerably decreases ore and coal requirements as raw resources [171]. Furthermore, various corporates have implemented such CE strategies and attained economic benefits, such as Phillips Inc. who claimed that employing refurbishment in medical systems lowered 28% of carbon emissions [172]. Thus, CE strategies not only

uplift economic aspects but also benefit the environmental sector by reducing pollution and protecting resource degradation.

Environmental benefits of CE approaches are significant. CE strategies reduce greenhouse gas emissions by diverting waste from landfills, where methane—a potent contributor to global warming—is generated [173]. Figure 7 depicts a relationship between CE and greenhouse and/or carbon emissions that influences CE strategies to be amended based on interrelation. Recycling and material reuse conserve natural resources, reduce extraction-related environmental impacts, and lower energy consumption [13]. Biological treatments, such as AD, generate biogas for energy while recycling nutrients, and composting improves soil health. Thermochemical processes, including pyrolysis and plasma-assisted treatments, allow energy and material recovery with minimal emissions, supporting climate change mitigation. Lifecycle assessments indicate that CE approaches achieve net reductions in carbon footprint, energy consumption, and pollutant loads compared with conventional linear waste management systems [82,174]. These environmental gains directly support SDG 7 (affordable and clean energy), SDG 11 (sustainable cities), and SDG 13 (climate action).

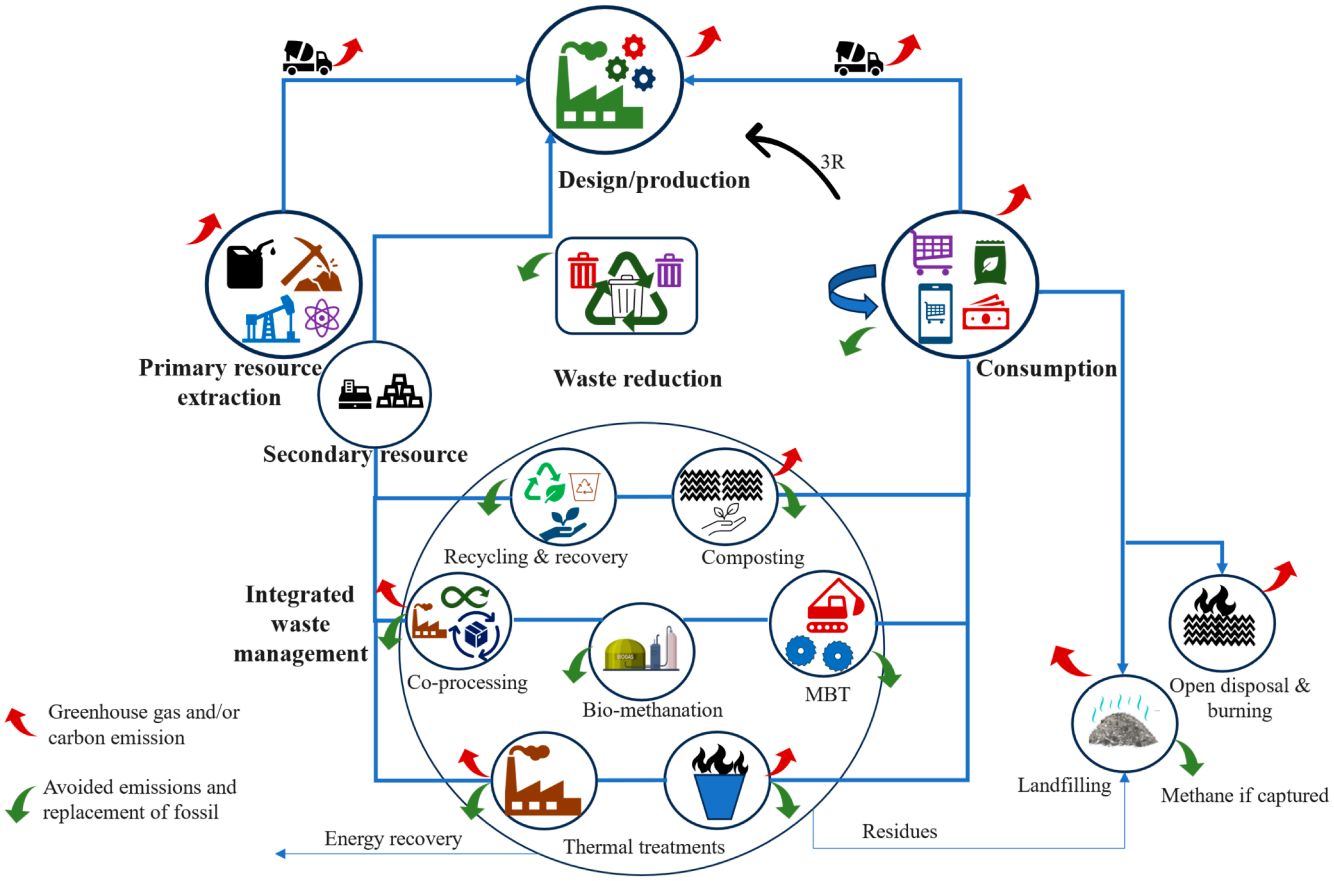


Figure 7. Relationship between CE and greenhouse and/or carbon emissions.

CE measures can positively impact material recovery from waste and protect natural resources. Sverko Grdic et al. [175] recommended CE measures for economic growth and conservation of natural resources. Pavolová et al. [176] suggested the optimization of the CE model through the partial substitution of secondary raw materials in place of primary ones, allowing a considerable decrease in natural resource consumption. Recently, Abad-Segura et al. [144] recommended coupling bioeconomy with CE to efficiently utilize natural resources. For example, the CE has proven advantageous in the E-waste treatment sector. A case study in India showed that E-waste has extensive potential for metal recovery before disposal [138]. The e-waste recycling facility in Karnataka, India, with a capacity of

10 ton/day and land area of 1.5 acres, is maintained by 100 employees. This facility recovers precious metals, cathode ray tubes, television glass screens, and electronic boards by full-scale deployments of collection, dismantling, processing and metallurgical units. Similar to e-waste, end-of-life photovoltaic (PV) panels, wind turbine blades, lithium-ion batteries, and multilayer composite materials would most likely be imposing a tough challenge to implement CE systems in next 5 years [177]. It is reported that due to the excessive increase in e-waste production from 62 million tons (year 2022) to 82 million tons (forecasted for year 2030), recycling rates have already reduced below 25%, projecting significant resource loss and environmental risk [178]. In view of present renewable energy sector promotion, PV solar panels, wind turbines and battery waste are greatly increasing. As per a recent report, global PV panel waste may produce 60–80 million tons by the year 2050 [177]. Moreover, due to thermosetting material being used in the manufacturing of wind turbine blades, this imposes reduced recyclability with conventional recycling methods, thereby reinforcing serious challenges in CE implementation. Additionally, Li-ion battery waste from electric vehicles and energy storage systems exhibits surprise fire eruptions, toxic substance release, and recovery of vital metals such as Li, Ni, and Co [83]. Thus, considering challenges associated with e-waste, battery waste and wastes from PV panels and wind turbine blades, the CE initiatives must ensure advanced or AI-enabled material recovery facilities, chemical recovery systems, eco-design strategies and EPR policy enforcements for supporting net-zero targets.

By combining energy and material recovery with sustainable resource management, CE strategies not only reduce environmental impacts but also promote long-term economic and social benefits [178]. This holistic perspective is essential for transitioning from a linear to a circular model, ensuring that waste is treated as a resource rather than a problem [137,140–142].

GHG emissions resulting from improper waste management pose significant environmental and public health risks. Recent years have seen notable progress in reducing these emissions globally. In the European Union (EU), the Circular Economy Action Plan [179] promotes a shift from linear to circular models and emphasizes recycling as a key tool for reducing GHG emissions. The EU environment action plan implements different waste management strategies and policies to enhance reuse and recycling. The Waste Framework Directive (2008/98/EC) noted by Gharfalkar et al. [180] recommends that member countries attain at least a 50% recycling rate for MSW. New targets have also been provided to be achieved by 2035. Landfill disposal will gradually be replaced by reuse and recycling in the coming years. A high recycling rate reduces landfilling loads for municipalities and promotes emissions reduction. For example, Figure 8 shows that product manufacturing through recycling and CE approaches significantly reduces emissions [181]. In recent years, the total MSW disposal in EU member states going for landfilling between 1995 and 2017 has been reduced by 60% through extensive recycling measures [182]. Although recycling emits fewer carbon and GHG emissions than incineration and landfilling, net emissions savings might be reliant on the type of recycled material. Thus, Balkau et al. [140] recommended the inclusion of lifecycle assessment coupled with recycled concepts for better environmental health.

Despite these benefits, challenges remain in regions with poor waste segregation, limited infrastructure, or low environmental awareness. Maintaining recycled material quality, ensuring energy-efficient processes, and encouraging sustainable consumer behavior are critical concerns [125]. Economic and behavioral incentives such as revenue from recovered materials, lower landfill costs, education programs, and user-friendly recycling infrastructure can improve adoption feasibility in such contexts. For example, a case study in Sweden on co-polyester plate recycling demonstrated that a closed-loop system achieved a 20–60% reduction in GHG emissions and a 50–60% reduction in energy requirements

compared to conventional recycling, while still meeting food safety standards [183]. These findings demonstrate that well-designed recycling systems can be both environmentally sustainable and economically viable, even in areas facing budgetary, infrastructural, and behavioral challenges.

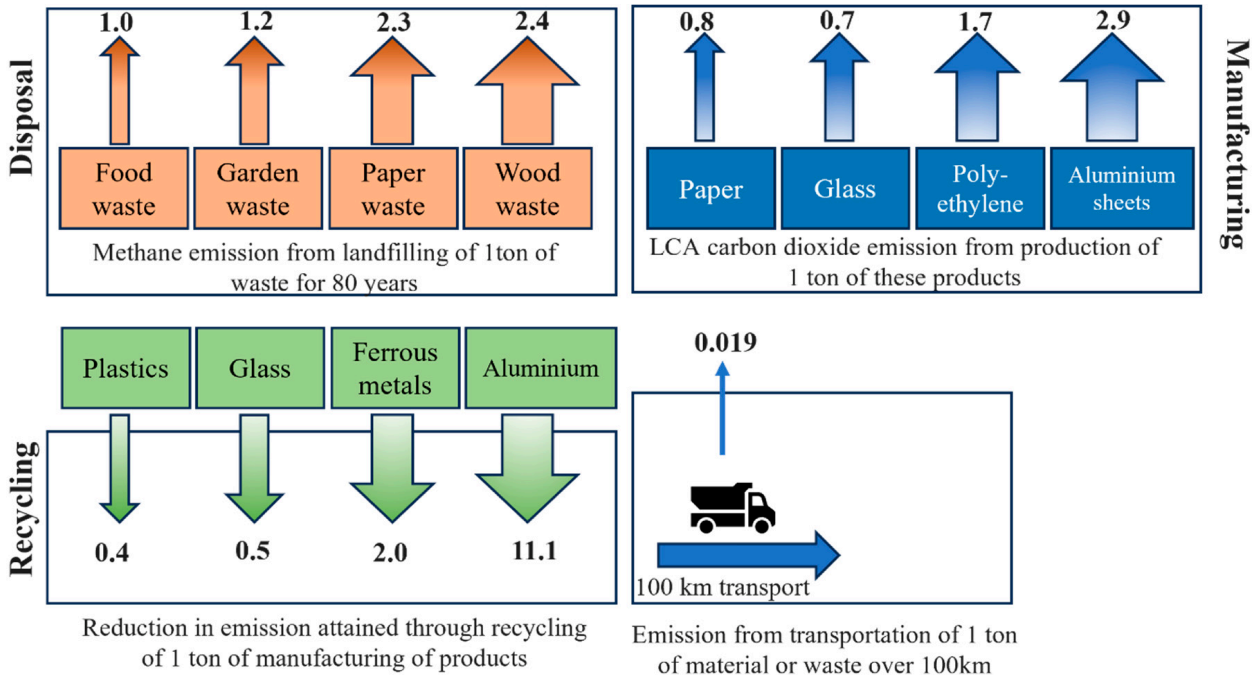


Figure 8. Analytical evidence of GHG emissions and mitigation potential through recycling measures for manufacturing, disposal and recycling different materials.

Implementing sustainable waste management solutions to reduce GHG and carbon emissions has become an urgent global priority. In the context of the SDGs under Agenda 2030, goals such as affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and climate action (SDG 13) are closely aligned with the development of energy-efficient and environmentally responsible waste management systems [184]. Despite international policy obligations, growing waste generation, inadequate waste segregation facilities, landfilling obligation, and inadequate infrastructure continue to hamper several SDG targets related to sustainable cities, responsible consumption, and climate mitigation, more prominently in developing countries. As numerous SDGs become progressively tougher to attain by the year 2030, integrated CE agendas including AI-driven assessment, decentralized resource recovery systems, policy-backed landfill alteration, and industrial symbiosis could exhibit a vital role in determining a prolonged or post-2030 sustainability transition. However, globally, numerous efforts have been made to reduce emissions and energy consumption in recycling and waste management. Since landfilling and deforestation contribute approximately 25% of global GHG emissions, promoting waste recycling can reduce landfill dependence and encourage the reuse of materials, thereby lowering emissions associated with manufacturing and procurement of virgin resources [29,42]. The CE strategies, combined with lifecycle assessment (LCA) approaches, have the potential to reduce global GHG emissions by 10–15% [140,176]. The summary of comparative LCA-based GWP investigation of various waste processing technologies is presented in Table 8. Despite being advantageous, there exist numerous challenges and bottlenecks for CE implementation at various levels. Elaborated insights associated with benefits and challenges of CE implementation are discussed in subsequent sections.

Table 8. Comparative LCA-based global warming potential (GWP) assessment of major waste treatment technologies.

Treatment Method	LCA Technique	Key Assumptions/System Boundary	Major Emission Sources and Reported GWP	Net-Zero Pathways	Reference
Landfilling	Cradle-to-grave attributional LCA	Inventory is offset by electric energy potential from landfill gas and leachate management system	Fugitive methane, emission from hauling trucks, particulate matter; GWP: 400–1200 kg CO_2-eq/t_{MSW}	Least supportive way because of GHG emission and higher inventory cost	[185]
WtE incineration plant (conventional)	Attributional LCA	Incorporated energy credits, heat recovery from flue gas and combustion units	Flue gas emission: CO_2, NOx, GWP: 200–600 kg CO_2-eq/t_{MSW}	Moderately favorable due to electric energy compensation	[186]
Gasification	Consequential/process-based LCA	Includes syngas yield, flue gas treatment, electric energy production	Syngas treatment, electric energy production, tar management; GWP: 50–350 kg CO_2-eq/t_{MSW}	Syngas utilization is favorable for net-zero goals	[187]
Plastic waste pyrolysis	Cradle-to-gate LCA	Segregated plastic from MSW, liquid fuel production, pyrolysis designed reactor	Electric energy consumption, char disposal; GWP: 100–450 kg CO_2-eq/t_{MSW}	Potentially supportive if liquid fuel substitutes conventional fuels	[188]
AD	Attributional LCA	Incorporates biogas production, digestate recovery, excludes fertilizer recovery	Leaking methane, digestate mismanagement; GWP: 50–250 kg CO_2-eq/t_{MSW}	Highly favorable due to bioenergy and nutrient recovery	[189]

4.2. Challenges in Circular Economy Implementation

4.2.1. Technological, Infrastructure, and Scalability Challenges

The successful implementation of CE strategies depends not only on technological innovation and supporting infrastructure but also on their scalability and adaptability across diverse contexts [190]. Technological barriers include high upfront investment costs, limited availability of advanced recycling facilities, and insufficient integration of digital monitoring tools. Infrastructure-related challenges are particularly acute in regions with weak waste management systems, where collection and sorting inefficiencies hinder CE adoption [172]. Equally important is the question of scalability and universal applicability. CE approaches cannot be implemented as a one-size-fits-all solution, as their success is shaped by geopolitical, economic, and environmental conditions. In developed regions, large-scale adoption is often facilitated by advanced industrial symbiosis networks, digital traceability, and extended producer responsibility schemes. In contrast, in developing or resource-constrained contexts, scalable solutions may emerge from strengthening informal recycling sectors, promoting local repair systems, and supporting resource-sharing initiatives that demand lower capital investment [146].

Adaptability can be enhanced by embedding local knowledge, cultural practices, and governance structures into CE strategies. International collaboration, pilot projects, and knowledge exchange platforms are essential to test transferability before widescale replication [191]. By addressing technological, infrastructural, and contextual barriers together, CE initiatives can move beyond conceptual frameworks to achieve both local relevance and global impact. Furthermore, technological limitations, high capital costs, and inadequate infrastructure pose significant challenges, particularly in developing regions. For example, low-income countries lack infrastructural facilities for waste collection which leads to merely ~48% of MSW collection and segregation in cities and less than 26% in villages, leading to only ~4% of waste recycling in low-income countries [192]. This reflects the fundamental infrastructural gap that prevents CE implementation at the source. To bridge these gaps, scalable and context-specific solutions are essential. These include manual or semi-automated sorting, community-based recycling programs, modular or mobile recycling units, and gradual adoption of advanced technologies through phased implementation and supportive policies [178]. Pilot projects and demonstration units provide practical roadmaps for infrastructure development, while

training municipal personnel ensures local capacity building. Moreover, integration with existing landfill-reliant systems is crucial to avoid operational disruptions. Phased adoption of recycling and material recovery alongside landfill operations allows smooth transitions without reducing efficiency. Waste-to-energy co-processing, pilot projects, and targeted training of municipal personnel further facilitate integration while minimizing risks of disruption. These strategies provide actionable pathways for aligning CE initiatives with current waste management infrastructures [193].

In addition, scalability and economic feasibility are critical for translating CE approaches from pilot projects to industrial applications [194]. The CE could fetch up to ~€1.8 trillion per annum in net profits by 2030 if broadly employed, against usual practices. Nevertheless, the transition costs including research and development, asset conservation, aids, digital setup, and stranded linear assets are sizable and uncertain, acting as an economic barrier for industry-wide adoption. On the other hand, technical feasibility is demonstrated at smaller scales: scaling requires careful evaluation of capital and operational costs, energy recovery efficiency, and potential revenue streams from recovered materials. Economic incentives, policy support, and public–private partnerships can enhance feasibility, while phased implementation allows industries to adapt gradually, mitigating financial and operational risks [195]. By considering economic viability alongside technical, social, and ethical factors, CE strategies can achieve long-term adoption at regional and industrial scales [194]. By providing actionable pathways, inclusive strategies, and ethical safeguards, even regions with underdeveloped infrastructure can adopt CE technologies while minimizing social disruption and environmental trade-offs, ensuring equitable and sustainable waste management solutions. Successful CE implementation requires overcoming interdisciplinary challenges through active collaboration across economics, engineering, policy, and social sciences. Cohesive solutions can be achieved by establishing stakeholder workshops, cross-sector working groups, and participatory planning processes that engage municipal authorities, industry representatives, researchers, and local communities [120]. This approach ensures that technological innovations, economic incentives, regulatory frameworks, and social behavior interventions are aligned, creating practical, socially equitable, and environmentally sustainable CE strategies. The consolidated scenarios of technological, infrastructure, and scalability challenges and their co-factors influencing CE strategies are displayed in Figure 9.

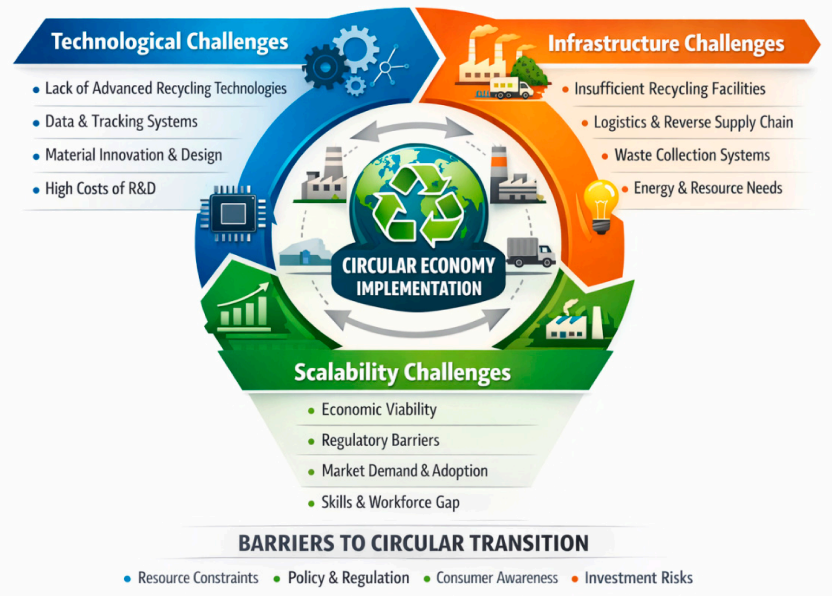


Figure 9. Technological, infrastructure, and scalability challenges while implementing CE strategies.

4.2.2. Socio-Economic, Cultural, Ethical, Political and Unintended Consequences

The success of CE approaches heavily depends on consumer behavior and cultural acceptance. Deep-rooted habits, low environmental awareness, and resistance to change can impede effective recycling and waste reduction [196]. To address these challenges, actionable strategies are essential, including targeted education and awareness campaigns, user-friendly recycling infrastructure, financial or social incentives (e.g., deposit-return schemes, rewards for recycling), and media campaigns highlighting successful initiatives. Policy measures, such as mandatory recycling regulations, coupled with community engagement programs that foster social norms around waste reduction, can reinforce behavioral change [197]. Engaging local leaders, schools, and civil society organizations ensures that interventions are culturally relevant and widely adopted. By implementing these strategies, CE initiatives can move from theoretical models to practical, socially supported solutions that achieve measurable environmental benefits [198].

Effective CE adoption requires strong and coherent policy and regulatory frameworks that create clear incentives for participation and compliance. These include economic instruments (subsidies, tax breaks, and financial support for recycling and waste-to-energy projects), regulatory mandates (mandatory recycling quotas, extended producer responsibility schemes, and landfill taxes), and governance mechanisms (stakeholder engagement platforms, monitoring tools, and public–private partnerships) [199,200]. In politically fragmented or economically constrained regions, phased implementation through pilot projects and localized initiatives can demonstrate tangible benefits, thereby fostering trust and encouraging broader uptake. Beyond technical and economic measures, policy guidance must anticipate and mitigate unintended consequences. CE transitions risk creating negative outcomes if poorly managed, such as the displacement of informal waste workers, the intensification of natural resource exploitation for recycling inputs, or the creation of unequal market advantages that marginalize vulnerable actors [195]. To address this, regulatory frameworks should be paired with inclusive social policies that formalize the role of informal waste workers, provide retraining and employment opportunities, and safeguard livelihoods [201].

Equally important are ethical considerations to ensure that low-income communities and marginalized populations do not bear disproportionate costs of CE implementation. Inclusive policies should integrate vulnerable groups into formal recycling systems, guarantee access to training and financial support, and enable participatory decision-making processes. To promote global equity, measures must also extend to developing nations through financial and technical assistance, capacity-building programs, structured knowledge transfer from developed economies, and equitable access to technology and infrastructure. Such initiatives prevent resource-constrained regions from being overburdened while ensuring that CE benefits—economic, environmental, and social—are shared fairly across nations, reinforcing the ethical foundation of CE adoption [202]. By embedding actionable policy insights alongside ethical safeguards, CE frameworks can move beyond theoretical models to become practically implementable, socially just, and globally equitable strategies for sustainable development. Further, accurately evaluating the long-term impact of CE strategies requires comprehensive measurement, accountability, and economic assessment [203]. A detailed LCA is essential to rigorously compare the environmental impacts of CE approaches versus traditional landfill-based waste management, including carbon footprint, resource use, pollution, and energy consumption across the entire supply chain. Continuous monitoring of landfill gas emissions, tracking recycling and material recovery rates, and incorporating cost–benefit analyses complement the LCA, providing a holistic picture of environmental, social, and economic performance. Variations in waste composition, regional policies, and socio-economic contexts can be addressed through site-specific emis-

sion factors, scenario-based modeling, and periodic audits. Given the urgency of climate action, timeframe considerations are critical. While full CE adoption may require several years, interim measures such as enhanced landfill gas capture, source segregation, rapid recycling initiatives, and waste-to-energy technologies can deliver immediate reductions in greenhouse gas emissions while facilitating a gradual, sustainable transition to circular waste management [204].

To ensure long-term sustainability in the context of population growth and increasing urbanization, CE strategies must be scalable and adaptable. Modular and flexible recycling infrastructure, continuous reassessment of waste flows, iterative LCA, and adaptive policy frameworks allow systems to expand capacity and integrate technological upgrades as waste generation increases [205]. Despite their benefits, CE strategies may entail unintended consequences, including increased energy consumption, overexploitation of natural resources due to rising demand for recycled materials, and displacement of informal workers dependent on landfills. Addressing these risks requires a holistic systems approach that integrates LCA, scenario-based modeling, inclusive stakeholder engagement, economic analysis, and adaptive management. By combining comprehensive LCA, robust measurement, short-term interventions, and proactive monitoring of potential trade-offs, CE strategies can maximize environmental, social, and economic benefits, ensure long-term sustainability, and maintain alignment with the SDGs—even under the pressing demands of the climate crisis [206].

Potential unintended consequences must also be acknowledged and mitigated. Transitioning toward formalized CE systems may displace informal waste workers who play a crucial role in local recycling economies. If not managed inclusively, this could lead to social exclusion and loss of livelihoods. Large-scale recycling efforts could unintentionally increase exploitation of natural resources, particularly if secondary material recovery drives unsustainable mining or energy-intensive processing [207]. Addressing these risks requires policies that integrate social protection measures, such as re-skilling programs, inclusion of informal workers in formal value chains, and strict environmental safeguards. Although CE strategies reduce environmental impacts, unintended consequences and trade-offs may occur. Increased demand for recycled materials could lead to overexploitation of certain resources, and formalizing recycling systems may displace informal workers who rely on landfills [208]. Additionally, energy consumption and emissions from recycling processes could partially offset the benefits of reduced landfill use. To address these challenges, a holistic systems approach is essential. This includes using LCA to quantify emissions, energy use, and resource consumption, applying scenario-based modeling to evaluate different CE pathways, engaging stakeholders to ensure inclusivity of vulnerable populations, and monitoring outcomes to enable adaptive management. By integrating these measures, CE strategies can maximize environmental and social benefits while minimizing negative trade-offs, ensuring a sustainable and realistic transition from landfill-dependent systems [209]. A consolidated depiction of benefits and challenges is presented in Figure 10 that conveys how CE initiatives could be influenced by other factors and what specific goals could be attained.

The informal sector plays a significant role in the waste management of developing countries by recycling usable materials, decreasing landfill waste, and augmenting CE pathways [201]. However, with the current shift in AI and automation in waste management systems, this could inadvertently depose informal waste workers if social protections are not synthesized into CE transitions, which may disturb another socially relevant SDG. Hence, CE implications must not be only assessed through potentials of resource recovery, technological advancements, carbon capture and climate change mitigation solutions, but also through the values of social circularity and just-transition governance. An inclusive

CE system must have the scope of including informal waste workers into existing formal waste management systems via cooperative recycling and municipality involvements, providing access to material recovery facilities and EPR-linked recycling systems. Moreover, occupational health and safety, social security, skill upgradation, and technology education are imperative to ensure active involvement in current tech-driven waste management. Adequate education regarding tech-driven system and AI enables technology use, and its handling procedures may also improve skilled labor wages, thereby balancing CE strategies and modernization with social circularity implications, especially in global south regions.

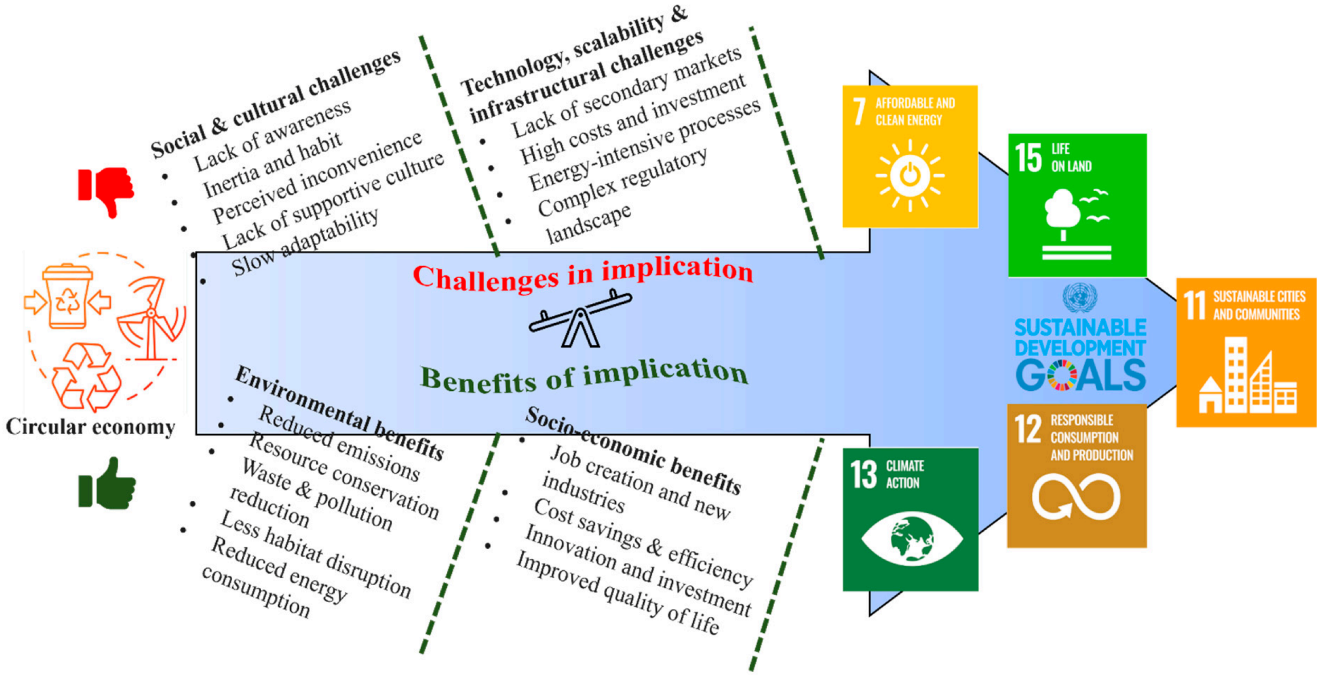


Figure 10. A summary of circular economy implementation—its benefits and challenges towards sustainable development.

For instance, the SWaCH model was launched by Pune municipality (India) for integrating ragpickers into formal waste collection system, incorporating more than 3500 informal waste pickers for door-to-door waste collection from 8 lakh households while formalizing their works with stable wages and occupational health and safety [210]. Analytical studies revealed that integration of informal workers into formal CE strategies could comprehensively augment recycling efficiency at significantly lower investments than completely privatizing the operation [211].

In summary, CE promotion is restrained by consistent challenges as discussed. Overcoming these barriers and the successful implementation of CE solutions necessitate adaptive and data-driven techniques competent in managing complex waste systems. In this shift, data-driven modeling such as artificial intelligence (AI) and machine learning (ML) could play a critical supporting role. The AI-driven waste sorting systems attain substantial classification precision, considerably advancing material recovery and recycling [212,213]. Moreover, the AI-driven pathway for carbon emission prediction and its optimization benefits the environment and demonstrates successful CE placement. Moreover, the ML models for waste generation prediction, emission modeling and forecasting could support better infrastructure planning. Hence, such advances provide AI–ML within this role, demonstrating existing solutions, challenges, and how it helps in implementing CE strategies to mitigate climate change impacts which are imperative to discuss comprehensively.

5. Role of AI in Circular Economy and Climate Change Mitigation

Recent advances in ML and AI offer new opportunities to strengthen CE strategies [212]. The ML algorithms are increasingly applied to predict waste generation, optimize collection routes, and improve the efficiency of recycling and recovery systems [214]. Image recognition models, for example, enable more accurate and automated waste segregation, reducing contamination in recycling streams. Similarly, predictive ML models are used to optimize biological processes such as AD and gasification, thereby maximizing energy and hydrogen yields while minimizing emissions [179,180,184]. By integrating data-driven decision-making with CE principles, urban systems can achieve higher efficiency, lower costs, and greater environmental benefits. Nevertheless, challenges such as data availability, interoperability, and governance remain, highlighting the need for collaborative frameworks that combine CE policies with digital innovations. Figure 11 depicts an overall scenario of implication of AI in waste management and eventually for climate change mitigation.

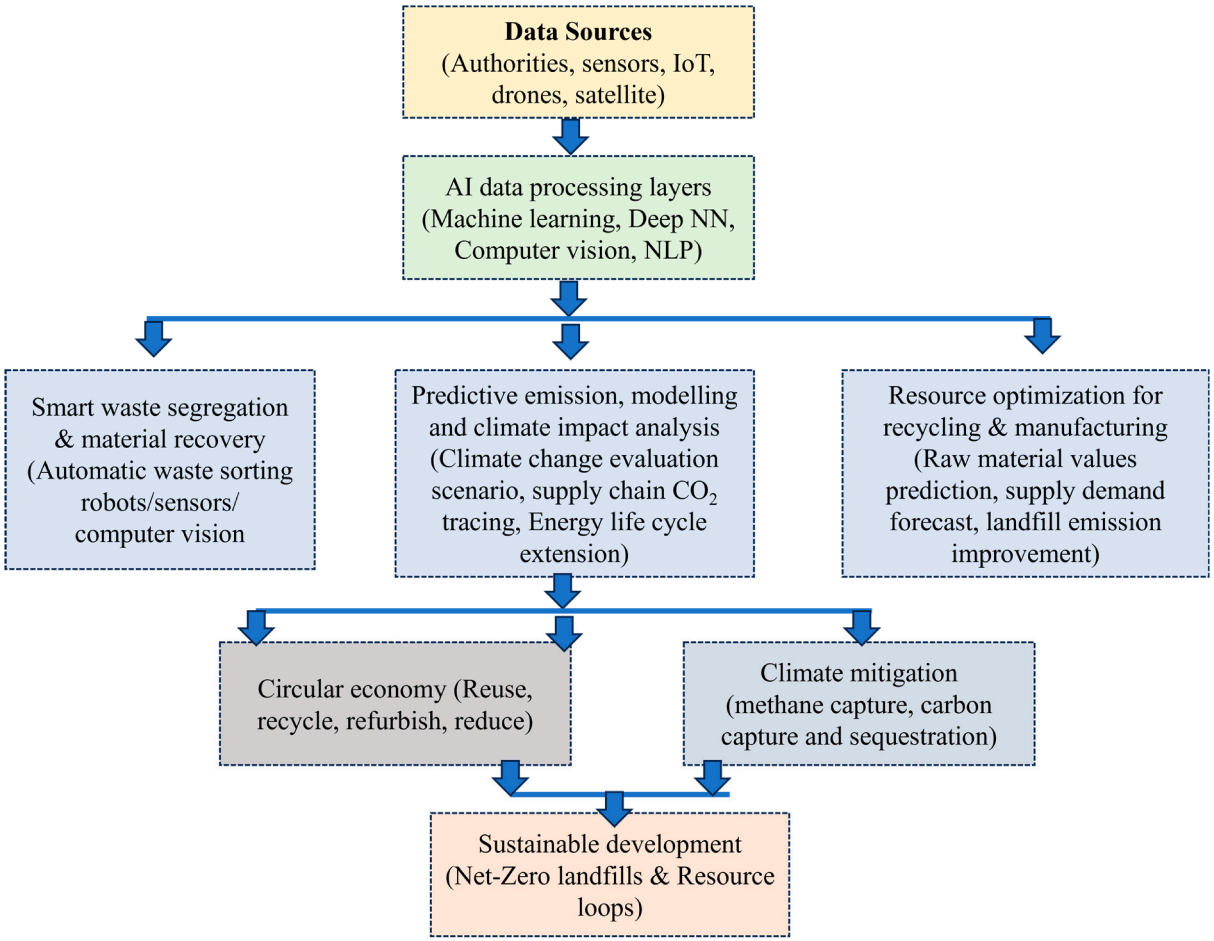


Figure 11. Role of AI in solid waste management, circular economy, sustainable development and mitigating climate change impacts.

AI is rapidly emerging as a transformative enabler of the CE, offering powerful solutions to optimize waste management, reduce environmental impacts, and mitigate climate change [212]. Digital technologies, including ML, Internet of Things (IoT), Big Data analytics, and AI-powered automation, can revolutionize landfill management, material recovery, and waste-to-energy systems, bridging the gap between conventional waste practices and sustainable circular solutions [135,214].

5.1. AI Applications in Landfill Operations

At the operational level, AI provides advanced tools for predictive monitoring and optimization of landfill processes, delivering significant environmental and economic benefits. ML and AI algorithms can analyze historical and real-time data from landfill sensors, waste composition records, meteorological inputs, and operational parameters to generate predictive insights. For example, AI models can forecast the production of methane, carbon dioxide, and other trace gases, allowing landfill operators to implement timely gas collection and treatment measures, thereby reducing greenhouse gas emissions and improving regulatory compliance [85]. Similarly, predictive algorithms can estimate leachate volumes and pollutant concentrations based on rainfall patterns, waste characteristics, and linear conditions, enabling operators to adjust collection and treatment systems to prevent soil and groundwater contamination. AI also facilitates the analysis of waste decomposition rates, identifying hotspots of accelerated or delayed organic matter degradation, which allows operators to optimize moisture content, aeration strategies, or cover placement, reducing odor, emissions, and leachate formation. Beyond monitoring, AI-powered automated sorting and recognition systems enhance CE practices by accurately identifying and separating recyclables such as plastics, metals, organics, and paper in real time, minimizing contamination and maximizing material recovery [84]. Integration with IoT-enabled sensors further supports continuous monitoring of temperature, humidity, gas composition, and leachate quality, with AI models providing actionable recommendations, real-time alerts, and dynamic operational adjustments. Collectively, these AI-driven approaches transform landfill management from a reactive to a proactive system, improving operational efficiency, reducing environmental impacts, extending landfill lifespan, and promoting CE principles by diverting valuable materials from disposal while mitigating climate change impacts.

AI plays a pivotal role in enhancing energy recovery from waste, including WtE and W2H processes, by optimizing operational parameters and reducing environmental impacts. Predictive machine learning models can analyze historical and real-time data on waste composition, temperature, moisture content, and reaction kinetics to determine the optimal conditions for AD, gasification, and pyrolysis systems, thereby maximizing energy output, improving hydrogen production, and lowering carbon dioxide emissions [84,215]. AI also enables process integration and resource allocation, linking waste generation patterns with potential energy recovery to design circular infrastructure that is both environmentally and economically efficient. By continuously analyzing process data, AI facilitates dynamic adjustments in feedstock ratios, residence times, and operational temperatures, ensuring maximum energy yield while minimizing pollutants and carbon footprints [216]. Additionally, AI-driven decision support tools assist policymakers, industries, and municipal stakeholders in selecting the most sustainable WtE/W2H strategies, evaluating trade-offs between energy recovery, emissions reduction, and material reuse [197]. Collectively, these AI applications transform conventional energy recovery processes into intelligent, adaptive systems, enabling a more resilient CE and contributing substantially to climate change mitigation and sustainable urban waste management. Table 9 summarizes applications of AI, techniques used, associated benefits, and key references in waste management systems.

AI can be implemented across multiple hierarchical levels to advance CE strategies and support climate change mitigation. At the micro level, individual organizations can deploy AI for tasks such as predictive monitoring, waste sorting, and process optimization, enabling efficient internal resource management, reducing operational costs, and minimizing environmental impacts. At the meso level, industrial clusters or municipal consortia can leverage AI to coordinate waste collection, recycling networks, and energy recovery infrastructure, fostering collaboration among stakeholders and enhancing system-wide

sustainability [168]. At the macro level, governments and regional authorities can utilize AI-driven decision support systems to guide urban planning, policy formulation, and circular infrastructure optimization, ensuring that CE strategies are aligned with national climate targets and Sustainable Development Goals (SDGs 7, 11, and 13) (Figure 12) [133]. By integrating AI across these hierarchical levels, stakeholders can create a holistic and adaptive circular system, enabling data-driven decision-making, enhancing resource efficiency, and strengthening the resilience of waste management systems while simultaneously contributing to global climate change mitigation efforts.

Table 9. Applications of AI, techniques used, associated benefits, and key references in waste management systems.

AI Application	Techniques	Outcomes/Benefits	Additional Insights (Implementation & Impact)	References
Waste collection	Smart bin systems (IoT-enabled)	Monitor fill levels; optimize collection timing and routes	Demonstrated reductions of 10–30% in collection trips in pilot smart-city deployments; enables demand-responsive services and lowers operational costs	[217]
	Route optimization (AI/OR)	Dynamic route adjustment; efficient fleet utilization	AI/metaheuristics outperform static routing under variable waste generation and traffic; supports integration with GIS and GPS data	[218,219]
	Dynamic scheduling	Adaptive collection schedules; reduced overflow events	Particularly effective in high-density urban areas with temporal variation in waste generation	[220]
Waste sorting	Automated & robotic sorting	Faster, more accurate separation of waste streams	Sorting accuracy commonly reported at 85–95% for major recyclables, significantly reducing contamination	[221]
	Sensor-based sorting—infrared hyperspectral	Improved material recognition	Complements vision-based AI for black plastics and multilayer materials	[222,223]
	Image recognition & machine vision	Real-time identification of waste categories	Enables deployment on conveyor belts and smart bins	[224]
Waste recycling	Material identification & sorting	Higher recycling efficiency; cleaner material streams	Directly improves economic value of recyclables and plant throughput	[224,225]
	Process optimization (ML)	Increased operational efficiency	ML-based control reduces downtime and energy use in recycling plants	[226]
	Quality control & inspection	Detection of contaminants and defects	Reduces rejected batches and downstream processing costs	[227]
	Robotics & automation	Labor-intensive tasks automated	Improves worker safety and consistency in high-throughput facilities	[228]
Waste monitoring	Predictive analytics	Forecast trends in waste generation and treatment needs	Supports long-term infrastructure planning and regulatory compliance	[229]
	Real-time data monitoring	Continuous tracking from generation to disposal	Enhances transparency and traceability across the waste chain	[230]
	Data-driven decision making	Evidence-based operational decisions	Integrates social, economic, and environmental data layers	[231]

5.2. Real-World Examples and Global Initiatives: Worldwide Insights, Challenges and Opportunities

Several global initiatives illustrate the practical role of artificial intelligence (AI) in advancing CE strategies and enhancing sustainability outcomes. In Ireland, AI applications across the waste, construction, and bio-economy sectors have facilitated circular practices, improved resource efficiency, and enabled data-driven policymaking, serving as a model for other regions seeking to integrate AI in CE processes [232]. In urban centers worldwide, the integration of AI with IoT technologies has optimized waste collection routes, automated sorting operations, reduced landfill volumes, and maximized recycling efficiency [233]. Predictive analytics allow municipalities to anticipate waste generation patterns, optimize energy recovery from WtE and W2H processes, and significantly reduce greenhouse gas emissions [234]. Moreover, the broader adoption of Industry 4.0 technologies, where AI is combined with IoT, Big Data, and cloud computing, enables seamless monitoring and optimization across multiple CE domains, including IS, supply chain circularity, and urban

metabolism. These real-world examples demonstrate that AI can effectively transform traditional waste management systems into intelligent, adaptive, and sustainable circular networks, supporting both environmental and economic objectives [200].

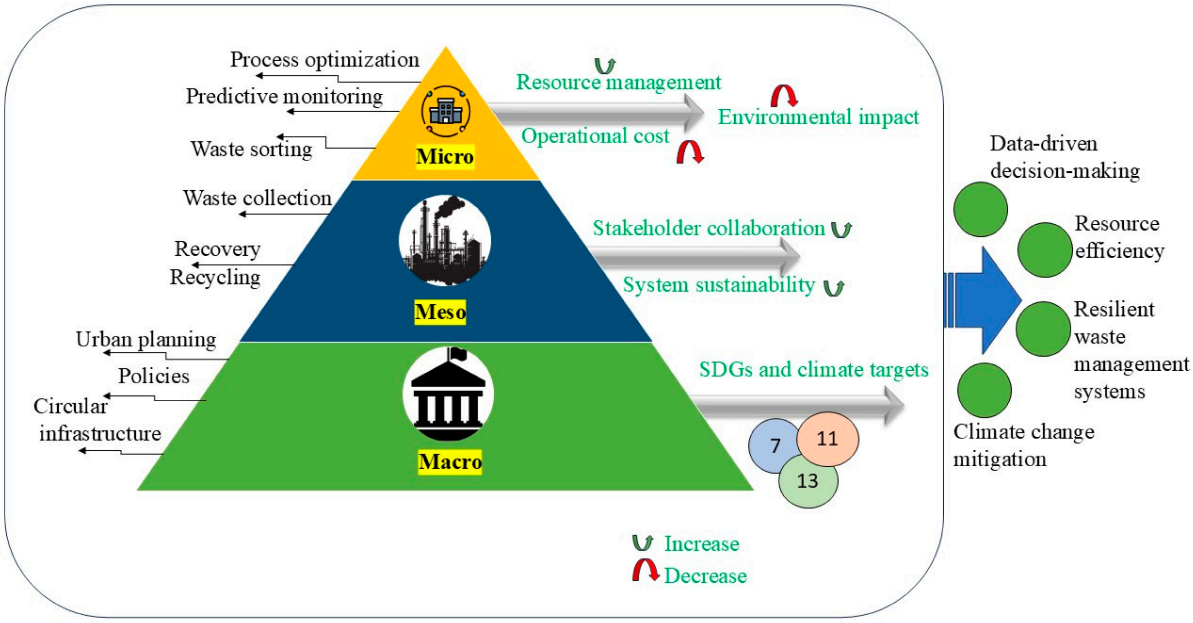


Figure 12. Hierarchical implementation of AI in aiding the circular economy and climate change reduction.

Despite the transformative potential of AI in CE applications, several challenges must be addressed to ensure effective implementation. Data availability and quality are critical, as predictive analytics and process optimization rely on high-resolution, continuous, and accurate datasets. Interoperability remains complex, requiring seamless integration of AI systems across diverse platforms, stakeholders, and infrastructures [235]. Furthermore, technical expertise and resource gaps including skilled personnel, financial investment, and institutional capacity can limit the design, deployment, and validation of AI-enabled solutions. Regulatory and policy alignment is essential, as coordinated governance frameworks must ensure that AI-driven CE practices comply with environmental regulations and sustainability targets [203,205]. Various countries/regions adopt distinct strategies and techniques for overcoming GHG emissions and their effects in order to combat climate change issues aroused due to waste management activities. The AI-based, data-driven modeling approaches, implemented for waste management techniques, contribution to circular economy, climate change mitigation, and respective challenges faced by various CE strategies, are listed in Table 10.

Regardless of the prominent role of AI in waste management and CE implications, various realistic and technical bottlenecks restrain its full-scale application. Scarcity of high-quality, precise and labeled datasets for solid waste streams, including multilayer plastics (MLPs), contaminated organic matter, construction and demolition waste, and commingles MSW, is one of the pivotal concerns for AI incorporation. MSW pertains to high heterogeneity and exhibits intense spatial and temporal variation relying on location, socio-economic practices, seasonal waste generation, and local segregation practices, unlike controlled industrial datasets. Subsequently, AI models developed for a region might not work in other locations, thus restricting model scalability. Such issues are dominant in developing countries where informal waste management systems are disintegrated and selectively operate waste segregation.

Moreover, deep learning and computer vision models adopted for waste classification and predictive optimization demand vast computational resources, largely annotated datasets and high-performance hardware [236]. The computational energy demand and associated carbon footprint of training complex AI architectures could often compensate for part of the environmental gains through process optimization or emission reduction. Hence, the effective sustainability advantages of AI implication should be verified using LCA and techno-economic assessment. Moreover, the lack of interoperability between AI platforms, IoT network, and MSW datasets impedes concurrent incorporation [237]. Existing research also often relies on lab-scale simulated datasets, while field-scale confirmation under dynamic waste conditions remains constrained [237–239]. Therefore, standardization of global datasets and region-specific calibration of AI models are imperative for vast implications.

Addressing these challenges creates significant opportunities to scale AI-enabled CE solutions, enhance operational efficiency, unlock environmental and economic benefits, and contribute meaningfully to climate change mitigation. By integrating predictive monitoring, automated sorting, energy recovery optimization, and data-driven decision-making, AI transforms conventional waste management into a circular, climate-smart system [197,240]. Its application across micro (individual organizations), meso (industrial clusters), and macro (governmental) levels facilitate the implementation of CE principles while supporting global Sustainable Development Goals (SDGs), including SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), and SDG 13 (climate action). In summary, AI not only strengthens CE practices but also accelerates the transition toward sustainable, resilient, and climate-friendly waste management systems worldwide.

Table 10. Artificial intelligence, data-driven modeling approaches implemented for waste management techniques, contribution to circular economy, climate change mitigation and challenges reported by recent studies.

S. No.	Study [Reference]	Quantitative Data Reported	AI Techniques Used	Key Outcomes	Contribution to Circular Economy & Climate Change Mitigation	Challenges & Limitations
1	Majchrowska et al. [241]—DL-based waste detection	~21,000+ annotated waste objects; improved detection accuracy across datasets	Convolutional Neural Network (CNN) -based object detection (YOLO/Faster R-CNN)	Accurate identification of waste in uncontrolled urban environments	Enhances CE by enabling efficient litter identification and segregation at source; indirectly reduces landfill disposal and associated GHG emissions through improved recycling rates	Dataset bias; small-object detection issues
2	Laksono et al. [242]—DL for inorganic waste sorting	High classification performance on packaging waste streams	Deep CNN with transfer learning	Improved automated segregation at waste processing sites	Supports CE by increasing recovery of recyclable packaging materials; lowers lifecycle emissions by avoiding virgin material production	Sensitivity to lighting and contamination
3	Shukhratov et al. [243]—Optical plastic detection	Conveyor-based real-time classification; reported precision metrics	CNNs + IoT video analytics	High-speed plastic identification for industrial sorting	Critical for plastic circularity: improves recycling efficiency, reduces plastic leakage to landfills and oceans, and lowers embodied carbon of plastics	Motion blur; hardware latency
4	Mehrdad et al. [244]—DL-based landfill methane prediction	Reduced RMSE in methane forecasting vs. baseline models	Deep learning (CNN/ Recurrent Neural Network (RNN) hybrids	Improved prediction of methane emissions and power generation	Strong climate mitigation impact: enables better landfill gas capture, reducing CH_4 (28 × CO_2 GWP) emissions and supporting energy recovery within CE	Data sparsity; site-specific tuning
5	Olawade et al. [245]—Smart waste management review	Synthesizes > 100 AI applications	CNNs, Random Forest (RF), Support Vector Regression (SVR), Genetic Algorithm (GA)	Identifies AI-driven efficiency gains across waste chain	Shows AI as a system enabler for CE—improving material recovery, reducing landfill dependence, and lowering emissions across collection, sorting, and processing	Lack of large-scale deployments
6	ACM study [246]—CNN waste classification	7 waste classes; accuracy metrics reported	CNN architectures [ResNet/Visual Geometry Group (VGG)]	Automated multi-class waste identification	Facilitates source separation, a cornerstone of CE, enabling higher recycling yields and reducing emissions from mixed-waste disposal	Class imbalance; limited field validation

Table 10. *Cont.*

S. No.	Study [Reference]	Quantitative Data Reported	AI Techniques Used	Key Outcomes	Contribution to Circular Economy & Climate Change Mitigation	Challenges & Limitations
7	Singh et al. [247]—ML for biogas optimization (India)	Multi-year AD plant data; improved R^2 and yield prediction	Random Forest, GBM, hybrid ML	Enhanced biogas production efficiency	Direct CE and climate benefit: increases renewable energy recovery from waste, offsets fossil fuels, and reduces uncontrolled methane release	Limited transferability
8	Nourani et al. [239]—ML-based MSW generation forecasting	Multi-year municipal datasets; reduced forecast error	Explainable ML (Mutual Information (MI) + Shapley Additive Explanations (SHAP) + ensembles)	More reliable waste generation prediction	Improves CE planning by aligning recycling and treatment capacity with future waste flows; avoids overcapacity and emission-intensive emergency disposal	Sensitive to socio-economic shifts
9	Lee et al. [248]—Waste forecasting (South Korea)	2000–2023 data; regional tonnage forecasts	SVR, RF, ensemble ML	Region-specific waste planning	Supports climate mitigation by enabling proactive infrastructure investments (recycling, WtE) and avoiding landfill expansion	Low temporal resolution
10	Thakur et al. [249]—Metaheuristic routing studies (2022–2025)	Route length & cost reductions reported (case-specific)	GA, SA, hybrid heuristics	Lower operational cost and emissions	Direct reduction in diesel use and GHG emissions; enhances CE logistics efficiency in material recovery systems	Requires real-time integration
11	Wang et al. [221] Smart recycling bin systems (CV-based)	Reported prototype accuracy	CNN + sensor fusion	Automated user-level sorting	Encourages behavioral change toward CE; reduces mixed waste disposal and lifecycle emissions	Cost and robustness
12	Cui et al. [250]—Integrated sorting & transport optimization	Cost and emission reductions in simulations	Optimization + Computer Vision (CV) + ML	System-level waste optimization	System-wide CE optimization: minimizes transport emissions while maximizing recovery and reuse efficiency	Scalability challenges

6. Conclusions and Recommendations

In current scenarios of urbanization, rapid population growth, and climate change, solid waste management remains a critical challenge worldwide. This review presents how strategic implementation of CE alternatives can transform conventional landfill dominates systems into sustainable, resource-efficient, and low-emission models. Implementation of landfill gas collection and recovery systems, energy production from waste, and improved recycling provide significant solutions for decreasing GHG emissions, preserving raw materials, and generating economic worth from otherwise discarded materials. A successful transition from linearity to circularity would mitigate environmental issues, augment sustainability in urban development, and nurture business opportunities for recycled materials. In order to accelerate this transition, advanced thermal and biological technologies should be integrated in existing solid waste management systems with robust policy interventions, strict governance and regulatory incentives, so that reliance on landfills could be reduced and plausible climate change impacts could be avoided.

The review also outlines that CE implementation in the waste management sector undergoes several challenges at multiple levels; hence, its solutions must be implemented at different levels. Therefore, a three-layered solution for CE promotion at micro, meso and macro levels needs to be implemented according to relevant requirements. Moreover, for actual realization of CE in the waste management sector, prospective research should focus on incorporating LCA studies, techno-economic evaluation and parametric optimization to evaluate the long-term performance of the proposed technologies. Secondly, the socio-economic outcomes of CE solutions, specifically on informal waste workers and demoted communities, should be assessed to safeguard inclusive and reasonable outcomes. Moreover, thermochemical conversion and biological technologies are vital in CE chains for handling combustible and biodegradable waste and produce valuable resources including syngas, biofuels, biomethane, etc., as prominent energy sources. However, their functioning as hybrid systems could be more crucial for increasing material and energy

recovery to reduce landfilling loads and consequent, obvious emissions from disposal sites. Furthermore, scalable frameworks that integrate technological solutions with policy, economic incentives, and social acceptance need to be designed and tested.

The roles of AI and ML in landfilling operations can predict long-term impacts of process intensification implemented in existing disposal streams. The integration of IoT-based monitoring of parameters and AI-based waste segregation can transform landfilling operations as the forecasting of datasets would lead to the development of upfront solution for foreseen problems. Predictive modeling should consider the waste generation and urbanization challenges as well for ensuring withstanding CE solutions. By referring these research targets, CE approaches can provide robust, scalable, and socially reasonable solutions, aiding directly to climate mitigation, resource efficiency, and the achievement of SDGs 7, 11, 12, 13 and 15.

The other recommendations of present review are as follows:

(i) Optimization of recovery and recycling: Investment in advanced waste sorting, recovery and reuse plans to augment material and energy recovery and reducing disposal dependence.

(ii) Deployment of integrated hybrid technologies: Integrated thermochemical, biological and mechanical treatments for attaining aggravated outcomes in line with sustainability goals.

(iii) Strengthen policy, governance, and incentive frameworks: Development and implementation of strict, robust policy interventions, economic benefits, and influential governance to reinforce CE adoption.

(iv) Incorporate social, ethical, and equity considerations: Ensure inclusive strategies that protect vulnerable populations, formalize informal workers, and promote equitable benefits.

(v) Promote innovation and future research: Explore emerging technologies, eco-design approach, area-specific waste impacts, lifecycle assessments, and adaptive strategies to advance sustainable urban waste management.

(vi) Policy recommendations: An integrated policy framework for simultaneously addressing CE and climate change mitigation solutions involving technological, socio-environmental and socio-economic measures is required at regional and national levels. Policies accounting for EPR must mandate producer responsibility from collection to end-of-life management of e-waste, battery waste, discarded PV panels and wind turbine blades, which need to be aided by digital tracing. Regarding landfill dependence and containing methane emissions, authorities must implement rigorous waste diversion targets, advancing landfill tax policy, carbon-crediting mechanisms associated with methane containment, and bioenergy recovery incentives.

(vii) Policy implications for decentralized CE systems including AD, material recovery units, and composting facilities should be promoted in the context of developing nations for better adaptability to waste heterogeneity. Moreover, IoT-enabled and AI-driven digital monitoring systems, GIS systems, and forecasting analytics must be endorsed through guidelines fostering waste data, concurrent waste monitoring, and smart governance. Further, techno-economic assessment should be compulsory prior to implementation of any CE solution to understand long-term sustainability rather than only relying on technological sophistication.

(viii) In view of social circularity, just-transition regulations should promote formal integration of the informal sector with formal CE systems while ensuring occupational health and safety, social security and skill-development of informal waste workers.

Author Contributions: Conceptualization, V.S.S.; methodology, A.N.S. and V.S.S.; software, A.K.V., R.P.K. and C.P.; validation, A.N.S., A.K.V., C.P., A.K.K. and J.F.; formal analysis, J.F., A.M., P.B. and M.B.; investigation, A.N.S., M.B., M.P. and V.S.S.; resources, M.P. and V.S.S.; data curation, A.N.S., A.K.V., R.P.K., C.P. and A.K.K.; writing—original draft preparation, A.N.S., A.K.V. and V.S.S.; writing—review and editing, A.N.S. and V.S.S.; visualization, A.N.S., M.B., M.P. and V.S.S.; supervision, V.S.S.; project administration, A.N.S., M.P. and V.S.S.; funding acquisition, A.N.S., M.P. and V.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Czech Academy of Sciences, grant number L100432402; the Ministry of Education, Youth and Sports of the Czech Republic, Specific University Research, grant number A1_FTOP_2023_001; Anusandhan National Research Foundation (ANRF), Department of Science and Technology (DST), Government of India as part of Prime Minister Early Career Research Grant (PM-ECRG) scheme, grant number ANRF/ECRG/2024/006195/ENS.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable.

Acknowledgments: V. Sikarwar gratefully acknowledges the support from the Czech Academy of Sciences. M. Pohořelý acknowledges the support from the Ministry of Education, Youth and Sports of the Czech Republic. Abhishek N Srivastava acknowledges financial support from Anusandhan National Research Foundation (ANRF), Department of Science and Technology (DST), Government of India as part of Prime Minister Early Career Research Grant (PM-ECRG) scheme.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Khan, S.; Anjum, R.; Raza, S.T.; Bazai, N.A.; Ihtisham, M. Technologies for municipal solid waste management: Current status, challenges, and future perspectives. *Chemosphere* **2022**, *288*, 132403. [CrossRef]
2. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef] [PubMed]
3. Chien, F.; Anwar, A.; Hsu, C.-C.; Sharif, A.; Razzaq, A.; Sinha, A. The role of information and communication technology in encountering environmental degradation: Proposing an SDG framework for the BRICS countries. *Technol. Soc.* **2021**, *65*, 101587. [CrossRef]
4. Shindell, D.; Ravishankara, A.R.; Kuylenstierna, J.C.I.; Michalopoulou, E.; Höglund-Isaksson, L.; Zhang, Y.; Seltzer, K.; Ru, M.; Castelino, R.; Faluvegi, G. *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions*; United Nations Environment Programm: Nairobi, Kenya, 2021.
5. Kusch-Brandt, S.; Sánchez Díaz, I.; Schröder, P. Circular economy solution pathways in the seventh UN Global Environment Outlook (GEO-7). *Waste Manag. Res.* **2026**, *44*, 233–236. [CrossRef]
6. Kristanto, G.A.; Koven, W. Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia. *City Environ. Interact.* **2019**, *4*, 100027. [CrossRef]
7. Cheng, X.; Zhang, L.; Li, W.; Long, R. Intentions and actions in household waste separation: A machine learning approach on the gap and determinants. *Environ. Impact Assess. Rev.* **2024**, *107*, 107566. [CrossRef]
8. Capoor, M.R.; Parida, A. Current perspectives of biomedical waste management in context of COVID-19". *Indian J. Med. Microbiol.* **2021**, *39*, 171–178. [CrossRef]
9. Patwa, A.; Parde, D.; Dohare, D.; Vijay, R.; Kumar, R. Solid waste characterization and treatment technologies in rural areas: An Indian and international review. *Environ. Technol. Innov.* **2020**, *20*, 101066. [CrossRef]
10. Han, Y.; Liu, J.; Xu, H. A comprehensive assessment of the performance of China's provincial zero-waste cities and impact factor diagnosis. *Environ. Impact Assess. Rev.* **2022**, *95*, 106778. [CrossRef]
11. Srivastava, A.N.; Chakma, S. Technologies and recycling strategies of municipal solid waste: A global perspective. In *Plastic Waste Management: Methods and Applications*; Wiley: Weinheim, Germany, 2024; pp. 339–362.
12. David, C.; Ganduri, J.; Ragunathan, V.; Natarajan, R. Characterization of pellets manufactured from plant waste and farm waste residues blended with distillery sludge as a prospective alternative fuel source. *Appl. Nanosci.* **2021**, *13*, 1235–1243. [CrossRef]
13. Nandhini, R.; Berslin, D.; Sivaprakash, B.; Rajamohan, N.; Vo, D.-V.N. Thermochemical conversion of municipal solid waste into energy and hydrogen: A review. *Environ. Chem. Lett.* **2022**, *20*, 1645–1669. [CrossRef]

14. Pham, C.Q.; Siang, T.J.; Kumar, P.S.; Ahmad, Z.; Xiao, L.; Bahari, M.B.; Cao, A.N.T.; Rajamohan, N.; Qazaq, A.S.; Kumar, A. Production of hydrogen and value-added carbon materials by catalytic methane decomposition: A review. *Environ. Chem. Lett.* **2022**, *20*, 2339–2359. [CrossRef]
15. Verma, S.K.; Kumar, R.; Mendiburu, A.; Thakur, A.; Gupta, L.; Gehlot, A.; Sikarwar, V. Experimental and numerical investigations with multifunctional heat transfer fluid to evaluate the performance of a thermal energy storage system. *Therm. Sci. Eng. Prog.* **2024**, *53*, 102717. [CrossRef]
16. Fathi, J.; Hlína, M.; Mates, T.; Buryi, M.; Sikarwar, V.; Mušálek, R.; Sharma, S.; Lojka, M.; Jiříčková, A.; Jankovský, O.; et al. Thermo-Chemical recycling of polypropylene via high-power microwave plasma gasification: Syngas and metal carbide production. *Chem. Eng. J.* **2025**, *511*, 161910. [CrossRef]
17. Srivastava, A.N.; Chakma, S. Landfill Gas Utilization. In *Handbook of Waste Biorefinery*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 807–811.
18. Srivastava, A.N.; Chakma, S. Quantification of landfill gas generation and energy recovery estimation from the municipal solid waste landfill sites of Delhi, India. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**, *46*, 7453–7466.
19. Xie, J.; Xia, Z.; Tian, X.; Liu, Y. Nexus and synergy between the low-carbon economy and circular economy: A systematic and critical review. *Environ. Impact Assess. Rev.* **2023**, *100*, 107077. [CrossRef]
20. Pan, Y.; Hashemizadeh, A. Circular economy-based assessment framework for enhancing sustainability in renewable energy development with life cycle considerations. *Environ. Impact Assess. Rev.* **2023**, *103*, 107289. [CrossRef]
21. Srivastava, A.N.; Chakma, S. Assessment of in situ stabilization and heavy metal toxicity reduction of sugar mill pressmud through pilot scale composting. *Environ. Monit. Assess.* **2023**, *195*, 951. [CrossRef] [PubMed]
22. Pires, A.; Martinho, G. Waste hierarchy index for circular economy in waste management. *Waste Manag.* **2019**, *95*, 298–305. [CrossRef]
23. Shah, H.H.; Amin, M.; Pepe, F. Maximizing resource efficiency: Opportunities for energy recovery from municipal solid waste in Europe. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 2766–2782. [CrossRef]
24. Åström, S. Perspectives on using cost-benefit analysis to set environmental targets—A compilation and discussion of arguments informed by the process leading to the 2016 EU air pollution emission targets. *Environ. Impact Assess. Rev.* **2023**, *98*, 106941. [CrossRef]
25. Arias, O.; Pulgar, J.A.; Soto, M. Application of organic wastes to soils and legislative intricacies in a circular economy context. *Clean Technol. Environ. Policy* **2022**, *24*, 1871–1888. [CrossRef]
26. Zhamiyeva, R.; Sultanbekova, G.; Balgimbekova, G.; Mussin, K.; Abzalbekova, M.; Kozhanov, M. Problems of the effectiveness of the implementation of international agreements in the field of waste management: The study of the experience of Kazakhstan in the context of the applicability of European legal practices. *Int. Environ. Agreem. Politics Law Econ.* **2022**, *22*, 177–199. [CrossRef]
27. Ramm, K. Considerations related to the application of the EU water reuse regulation to the production of snow from reclaimed water. *Circ. Econ. Sustain.* **2021**, *2*, 569–587. [CrossRef]
28. Amicarelli, V.; Rana, R.L.; Lombardi, M.; Fellner, J.; Tricase, C.; Bux, C. Material flow analysis and carbon footprint of water-packaging waste management. *Environ. Impact Assess. Rev.* **2024**, *106*, 107517. [CrossRef]
29. Kuci, A.; Fogarassy, C. European Green Deal Policy for the Circular Economy Opportunities and Challenges. Available online: https://real.mtak.hu/127569/1/39-2021-08-HAEDOI10.17676HAE.2021.39.65.pdf (accessed on 23 February 2026).
30. Srivastava, A.N.; Chakma, S. Investigating leachate decontamination and biomethane augmentation through Co-disposal of paper mill sludge with municipal solid waste in simulated anaerobic landfill bioreactors. *Bioresour. Technol.* **2021**, *329*, 124889. [CrossRef]
31. Cossu, R.; Grossule, V. *Landfill Bioreactors*; Elsevier Inc.: Amsterdam, The Netherlands, 2018. [CrossRef]
32. Srivastava, A.N.; Singh, R.; Chakma, S.; Birke, V. Advancements in Operations of Bioreactor Landfills for Enhanced Biodegradation of Municipal Solid Waste. In *Circular Economy in Municipal Solid Waste Landfilling: Biomining & Leachate Treatment*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 153–166.
33. Srivastava, A.N.; Chakma, S. Bioreactor landfills: Sustainable solution for disposal of municipal solid waste. In *Advanced Organic Waste Management*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 315–328.
34. Nabi, M.; Liang, H.; Cheng, L.; Yang, W.; Gao, D. A comprehensive review on the use of conductive materials to improve anaerobic digestion: Focusing on landfill leachate treatment. *J. Environ. Manag.* **2022**, *309*, 114540. [CrossRef]
35. Liu, H.-B.; Liu, S.-J.; He, X.-S.; Dang, F.; Tang, Y.-Y.; Xi, B.-D. Effects of landfill refuse on the reductive dechlorination of pentachlorophenol and speciation transformation of heavy metals. *Sci. Total. Environ.* **2021**, *760*, 144122. [CrossRef]
36. Wang, Y.; Xu, R.; Wang, H.; Shi, H.; Kai, Y.; Sun, Y.; Li, W.; Bian, R.; Zhan, M. Insights into the stabilization of landfill by assessing the diversity and dynamic succession of bacterial community and its associated bio-metabolic process. *Sci. Total Environ.* **2021**, *768*, 145466. [CrossRef]

37. Fisher-Wellman, K.H.; Davidson, M.T.; Narowski, T.M.; Lin, C.-T.; Koves, T.R.; Muoio, D.M. Mitochondrial Diagnostics: A Multiplexed Assay Platform for Comprehensive Assessment of Mitochondrial Energy Fluxes. *Cell Rep.* **2018**, *24*, 3593–3606. [CrossRef]
38. Cheng, J.; Dong, H.; Zhang, H.; Yuan, L.; Li, H.; Yue, L.; Hua, J.; Zhou, J. Improving CH4 production and energy conversion from CO_2 and H_2 feedstock gases with mixed methanogenic community over Fe nanoparticles. *Bioresour. Technol.* **2020**, *314*, 123799. [CrossRef]
39. Letey, J.; Valoras, N.; Focht, D.D.; Ryden, J.C. Nitrous oxide production and reduction during denitrification as affected by redox potential. *Soil Sci. Soc. Am. J.* **1981**, *45*, 727–730. [CrossRef]
40. Timoshnikov, V.A.; Kobzeva, T.V.; Polyakov, N.E.; Kontoghiorghes, G.J. Inhibition of Fe^{2+}- and Fe^{3+}- induced hydroxyl radical production by the iron-chelating drug deferiprone. *Free. Radic. Biol. Med.* **2015**, *78*, 118–122. [CrossRef] [PubMed]
41. El Awady, M.H.; Dahaba, A.A. Sulfate Reduction in an Upflow Anaerobic Sludge Blanket Bioreactor and Optimization of Operational Conditions: pH, Hydraulic Retention Time, Sulfate Loading Rate, COD/SO_4^{2-} Ratio. *Egypt. J. Chem.* **2023**, *66*, 379–386. [CrossRef]
42. Maria, C.; Góis, J.; Leitão, A. Challenges and perspectives of greenhouse gases emissions from municipal solid waste management in Angola. *Energy Rep.* **2020**, *6*, 364–369. [CrossRef]
43. Srivastava, A.N.; Chakma, S. Dry Tomb-Bioreactor Landfilling Approach for Enhanced Biodegradation and Biomethane Generation from Municipal Solid Waste Co-disposed with Sugar Mill Pressmud. *Bioresour. Technol.* **2021**, *342*, 125895. [CrossRef] [PubMed]
44. Li, P.; Karunanidhi, D.; Subramani, T.; Srinivasamoorthy, K. Sources and consequences of groundwater contamination. *Arch. Environ. Contam. Toxicol.* **2021**, *80*, 1–10. [CrossRef]
45. Nisbet, E.G.; Fisher, R.E.; Lowry, D.; France, J.L.; Allen, G.; Bakkaloglu, S.; Broderick, T.J.; Cain, M.; Coleman, M.; Fernandez, J. Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement. *Rev. Geophys.* **2020**, *58*, e2019RG000675. [CrossRef]
46. Yaashikaa, P.R.; Kumar, P.S.; Nhung, T.C.; Hemavathy, R.V.; Jawahar, M.J.; Neshaanthini, J.P.; Rangasamy, G. A review on landfill system for municipal solid wastes: Insight into leachate, gas emissions, environmental and economic analysis. *Chemosphere* **2022**, *309*, 136627. [CrossRef] [PubMed]
47. Meza, D.D.O.; Gutiérrez, A.S.; Eras, J.J.C.; Mendoza, J.S.; Ruydíaz, J.H. Techno-economic and environmental assessment of the landfill gas to energy potential of major Colombian cities. *Energy Convers. Manag.* **2023**, *293*, 117522. [CrossRef]
48. Sun, L.; Li, Z.; Fujii, M.; Hijioka, Y.; Fujita, T. Carbon footprint assessment for the waste management sector: A comparative analysis of China and Japan. *Front. Energy* **2018**, *12*, 400–410. [CrossRef]
49. Shen, S.; Chen, Y.; Zhan, L.; Xie, H.; Bouazza, A.; He, F.; Zuo, X. Methane hotspot localization and visualization at a large-scale Xi'an landfill in China: Effective tool for landfill gas management. *J. Environ. Manag.* **2018**, *225*, 232–241. [CrossRef]
50. Kormi, T.; Mhadhebi, S.; Ali, N.B.H.; Abichou, T.; Green, R. Estimation of fugitive landfill methane emissions using surface emission monitoring and Genetic Algorithms optimization. *Waste Manag.* **2018**, *72*, 313–328. [CrossRef] [PubMed]
51. Williams, J.P.; Ars, S.; Vogel, F.; Regehr, A.; Kang, M. Differentiating and mitigating methane emissions from fugitive leaks from natural gas distribution, historic landfills, and manholes in Montréal, Canada. *Environ. Sci. Technol.* **2022**, *56*, 16686–16694. [CrossRef]
52. Mønster, J.; Kjeldsen, P.; Scheutz, C. Methodologies for measuring fugitive methane emissions from landfills—A review. *Waste Manag.* **2019**, *87*, 835–859. [CrossRef]
53. Gaze, B.; Knutel, B.; Zając, K.; Jajczyk, M.; Bukowski, P. Comparison of selected technologies to improve the quality of exhaust gases from landfill gas combustion. *Energies* **2022**, *15*, 778. [CrossRef]
54. Su, Y.; Pei, J.; Tian, B.; Fan, F.; Tang, M.; Li, W.; He, R. Potential application of biocover soils to landfills for mitigating toluene emission. *J. Hazard. Mater.* **2015**, *299*, 18–26. [CrossRef] [PubMed]
55. Chetri, J.K.; Reddy, K.R. Advancements in municipal solid waste landfill cover system: A review. *J. Indian Inst. Sci.* **2021**, *101*, 557–588. [CrossRef]
56. Nikiema, J.; Brzezinski, R.; Heitz, M. Elimination of methane generated from landfills by biofiltration: A review. *Rev. Environ. Sci. Bio/Technol.* **2007**, *6*, 261–284. [CrossRef]
57. Ramirez, A.A.; García-Aguilar, B.P.; Jones, J.P.; Heitz, M. Improvement of methane biofiltration by the addition of non-ionic surfactants to biofilters packed with inert materials. *Process. Biochem.* **2012**, *47*, 76–82. [CrossRef]
58. Ferdowsi, M.; Veillette, M.; Ramirez, A.A.; Jones, J.P.; Heitz, M. erformance evaluation of a methane biofilter under steady state, transient state and starvation conditions. *Water Air Soil Pollut.* **2016**, *227*, 168. [CrossRef]
59. Khabiri, B.; Ferdowsi, M.; Benyoussef, E.H.; Malhautier, L.; Buelna, G.; Jones, J.P.; Heitz, M. Biofiltration of methane in presence of ethylbenzene or xylene. *Atmos. Pollut. Res.* **2022**, *13*, 101271.
60. Al-Heetimi, O.T.; Van De Ven, C.J.C.; Van Geel, P.J.; Rayhani, M.T. Performance of Biocover Materials in Mitigating Methane Emissions from Landfills under Different Loading Rates. *J. Environ. Eng.* **2023**, *149*, 4023035. [CrossRef]

61. Safari, E.; Al-Suwaidi, G.; Rayhani, M.T. Performance of biocover in mitigating fugitive methane emissions from municipal solid waste landfills in cold climates. *J. Environ. Eng.* **2017**, *143*, 6017003. [CrossRef]
62. Wei, X.-M.; Su, Y.; Zhang, H.-T.; Chen, M.; He, R. Responses of methanotrophic activity, community and EPS production to CH_4 and O_2 concentrations in waste biocover soils. *Waste Manag.* **2015**, *42*, 118–127. [CrossRef] [PubMed]
63. He, R.; Wang, J.; Xia, F.-F.; Mao, L.-J.; Shen, D.-S. Evaluation of methane oxidation activity in waste biocover soil during landfill stabilization. *Chemosphere* **2012**, *89*, 672–679. [CrossRef]
64. Kriipsalu, M.; Somani, M.; Pehme, K.; Tamm, O.; Truu, J.; Truu, M.; Orupold, K. Performance of biocover in controlling methane emissions from landfill: A decade of full-scale investigation. *Process Saf. Environ. Prot.* **2023**, *172*, 486–495. [CrossRef]
65. Brandt, E.M.F.; Duarte, F.V.; Vieira, J.P.R.; Melo, V.M.; Souza, C.L.; Araújo, J.C.; Chernicharo, C.A.L. The use of novel packing material for improving methane oxidation in biofilters. *J. Environ. Manag.* **2016**, *182*, 412–420. [CrossRef]
66. Karthikeyan, O.P.; Saravanan, N.; Cirés, S.; Alvarez-Roa, C.; Razaghi, A.; Chidambarampadmavathy, K.; Velu, C.; Subashchandrabose, G.; Heimann, K. Culture scale-up and immobilisation of a mixed methanotrophic consortium for methane remediation in pilot-scale bio-filters. *Environ. Technol.* **2016**, *38*, 474–482. [CrossRef]
67. Choi, H.; Ryu, H.W.; Cho, K.-S. Biocomplex textile as an alternative daily cover for the simultaneous mitigation of methane and malodorous compounds. *Waste Manag.* **2018**, *72*, 339–348. [CrossRef]
68. López, J.C.; Merchán, L.; Lebrero, R.; Muñoz, R. Feast-famine biofilter operation for methane mitigation. *J. Clean. Prod.* **2018**, *170*, 108–118. [CrossRef]
69. La, H.; Hettiaratchi, J.P.A.; Achari, G.; Verbeke, T.J.; Dunfield, P.F. Biofiltration of methane using hybrid mixtures of biochar, lava rock and compost. *Environ. Pollut.* **2018**, *241*, 45–54. [CrossRef]
70. Gebert, J.; Groengroeft, A.; Pfeiffer, E.-M. Relevance of soil physical properties for the microbial oxidation of methane in landfill covers. *Soil Biol. Biochem.* **2011**, *43*, 1759–1767. [CrossRef]
71. Reddy, K.R.; Yargicoglu, E.N.; Yue, D.; Yaghoubi, P. Enhanced microbial methane oxidation in landfill cover soil amended with biochar. *J. Geotech. Geoenvironmental Eng.* **2014**, *140*, 4014047. [CrossRef]
72. Yargicoglu, E.N.; Reddy, K.R. Effects of biochar and wood pellets amendments added to landfill cover soil on microbial methane oxidation: A laboratory column study. *J. Environ. Manag.* **2017**, *193*, 19–31. [CrossRef] [PubMed]
73. Parsaeifard, N.; Sattler, M.; Nasirian, B.; Chen, V.C.P. Enhancing anaerobic oxidation of methane in municipal solid waste landfill cover soil. *Waste Manag.* **2020**, *106*, 44–54. [CrossRef]
74. Niemczyk, M.; Berenjkar, P.; Wilkinson, N.; Lozecznik, S.; Sparling, R.; Yuan, Q. Enhancement of CH4 oxidation potential in bio-based landfill cover materials. *Process Saf. Environ. Prot.* **2021**, *146*, 943–951. [CrossRef]
75. Niemczyk, M.; Berenjkar, P.; Sparling, R.; Lozecznik, S.; Yuan, Q. Optimized design of a compost layer in a landfill biocover for CH4 oxidation. *Process Saf. Environ. Prot.* **2022**, *160*, 354–361. [CrossRef]
76. Sikarwar, V.S.; Reichert, A.; Jeremias, M.; Manovic, V. COVID-19 pandemic and global carbon dioxide emissions: A first assessment. *Sci. Total. Environ.* **2021**, *794*, 148770. [CrossRef]
77. Fei, F.; Wen, Z.; De Clercq, D. Spatio-temporal estimation of landfill gas energy potential: A case study in China. *Renew. Sustain. Energy Rev.* **2019**, *103*, 217–226. [CrossRef]
78. De Cian, E.; Wing, I.S. Global energy consumption in a warming climate. *Environ. Resour. Econ.* **2019**, *72*, 365–410. [CrossRef]
79. Zhang, J.; Fang, H.; Ma, B.; You, H. Study on Carbon Emissions from Municipal Solid Waste in Shenzhen. In *Proceedings of the 2015 International Symposium on Energy Science and Chemical Engineering*; Atlantis Press: Dordrecht, The Netherlands, 2015; pp. 232–235.
80. Srivastava, A.N.; Sikarwar, V.S. Cogeneration and trigeneration applications of methane conversion. In *Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 103–125.
81. Xie, L.; Li, T.; Gao, J.; Fei, X.; Wu, X.; Jiang, Y. Effect of moisture content in sewage sludge on air gasification. *J. Fuel Chem. Technol.* **2010**, *38*, 615–620. [CrossRef]
82. Pujara, Y.; Pathak, P.; Sharma, A.; Govani, J. Review on Indian Municipal Solid Waste Management practices for reduction of environmental impacts to achieve sustainable development goals. *J. Environ. Manag.* **2019**, *248*, 109238. [CrossRef]
83. Abba, A.H.; Babagana, U.M.; Atiku, A.A.; Burmamu, B.R. Evaluation of Energy Potentials from Municipal Solid Waste: A Case Study of Yola, Nigeria. *FUTY J. Environ.* **2019**, *13*, 36–45.
84. Materazzi, M.; Chari, S.; Sebastiani, A.; Lettieri, P.; Paulillo, A. Waste-to-energy and waste-to-hydrogen with CCS: Methodological assessment of pathways to carbon-negative waste treatment from an LCA perspective. *Waste Manag.* **2023**, *173*, 184–199. [CrossRef]
85. Sharma, G.; Dewangan, A.K.; Yadav, A.K.; Ahmad, A. Feasibility of waste-to-hydrogen generation system based on gasification/pyrolysis: A comprehensive review of experimental studies. *J. Therm. Anal. Calorim.* **2024**, *149*, 13629–13651. [CrossRef]
86. Sharifvaghefi, S.; Zheng, Y. Microwave vs conventional heating in hydrogen production via catalytic dry reforming of methane. *Resour. Chem. Mater.* **2022**, *1*, 290–307. [CrossRef]
87. Botla, G.; Barmavatu, P.; Pohorely, M.; Jeremias, M.; Sikarwar, V.S. Optimization of value-added products using response surface methodology from the HDPE waste plastic by thermal cracking. *Therm. Sci. Eng. Prog.* **2024**, *50*, 102514. [CrossRef]

88. Srivastava, A.N.; Kaviti, A.K.; Chakma, S.; Sikarwar, V.S. Solar and Biomass-Based Cogeneration Technologies. In *Encyclopedia of Renewable Energy, Sustainability and the Environment*; Elsevier: Amsterdam, The Netherlands, 2023. [CrossRef]
89. Maturi, K.C.; Madeti, S.R.K.; Sinha, S.; Saikia, S.; Srivastava, A.; Haq, I. Revolutionizing bio-hydrogen production: Smart integration of nanotechnology, microbial engineering, and circular waste valorisation. *Bioresour. Bioprocess.* **2026**, *13*, 17. [CrossRef] [PubMed]
90. Amponsah, N.Y.; Troldborg, M.; Kington, B.; Aalders, I.; Hough, R.L. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. *Renew. Sustain. Energy Rev.* **2014**, *39*, 461–475. [CrossRef]
91. Bandara, J.C.; Jaiswal, R.; Nielsen, H.K.; Moldestad, B.M.E.; Eikeland, M.S. Air gasification of wood chips, wood pellets and grass pellets in a bubbling fluidized bed reactor. *Energy* **2021**, *233*, 121149. [CrossRef]
92. Shehzad, A.; Bashir, M.J.K.; Sethupathi, S. System analysis for synthesis gas (syngas) production in Pakistan from municipal solid waste gasification using a circulating fluidized bed gasifier. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1302–1311. [CrossRef]
93. Chan, W.P.; Veksha, A.; Lei, J.; Oh, W.-D.; Dou, X.; Giannis, A.; Lisak, G.; Lim, T.-T. A hot syngas purification system integrated with downdraft gasification of municipal solid waste. *Appl. Energy* **2019**, *237*, 227–240. [CrossRef]
94. Kungkajit, C.; Prateepchaikul, G.; Kaosol, T. Influence of plastic waste for refuse-derived fuel on downdraft gasification. *Energy Procedia* **2015**, *79*, 528–535. [CrossRef]
95. Savuto, E.; Di Carlo, A.; Gallucci, K.; Di Giuliano, A.; Rapagnà, S. Steam gasification of lignite and solid recovered fuel (SRF) in a bench scale fluidized bed gasifier. *Waste Manag.* **2020**, *114*, 341–350. [CrossRef]
96. von Berg, L.; Pongratz, G.; Pilatov, A.; Almuina-Villar, H.; Hochenauer, C.; Scharler, R.; Anca-Couce, A. Correlations between tar content and permanent gases as well as reactor temperature in a lab-scale fluidized bed biomass gasifier applying different feedstock and operating conditions. *Fuel* **2021**, *305*, 121531. [CrossRef]
97. Lam, S.S.; Mahari, W.A.W.; Ok, Y.S.; Peng, W.; Chong, C.T.; Ma, N.L.; Chase, H.A.; Liew, Z.; Yusup, S.; Kwon, E.E. Microwave vacuum pyrolysis of waste plastic and used cooking oil for simultaneous waste reduction and sustainable energy conversion: Recovery of cleaner liquid fuel and techno-economic analysis. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109359. [CrossRef]
98. Ding, K.; Liu, S.; Huang, Y.; Liu, S.; Zhou, N.; Peng, P.; Wang, Y.; Chen, P.; Ruan, R. Catalytic microwave-assisted pyrolysis of plastic waste over NiO and HY for gasoline-range hydrocarbons production. *Energy Convers. Manag.* **2019**, *196*, 1316–1325. [CrossRef]
99. Jiang, G.; Wang, J.; Al-Salem, S.; Leeke, G.A. Molten solar salt pyrolysis of mixed plastic waste: Process simulation and technoeconomic evaluation. *Energy Fuels* **2020**, *34*, 7397–7409. [CrossRef]
100. Mahari, W.A.W.; Chong, C.T.; Cheng, C.K.; Lee, C.L.; Hendrata, K.; Yek, P.N.Y.; Ma, N.L.; Lam, S.S. Production of value-added liquid fuel via microwave co-pyrolysis of used frying oil and plastic waste. *Energy* **2018**, *162*, 309–317.
101. Beyene, H.D.; Werkneh, A.A.; Ambaye, T.G. Current updates on waste to energy (WtE) technologies: A review. *Renew. Energy Focus* **2018**, *24*, 1–11. [CrossRef]
102. Mayanti, B.; Songok, J.; Helo, P. Multi-objective optimization to improve energy, economic and, environmental life cycle assessment in waste-to-energy plant. *Waste Manag.* **2021**, *127*, 147–157. [CrossRef]
103. Srivastava, A.N.; Chakma, S. Hybrid bioreactor approach for enhanced valorization and heavy metal stabilization for co-digested municipal and agro-industrial solid wastes. *J. Water Process. Eng.* **2025**, *74*, 107763. [CrossRef]
104. Srivastava, A.N.; Sruthi, R.; Sikarwar, V.S. A review on fate and influence of micro-nano-plastics and bioplastics in anaerobic digestion: Mechanistic insights, prospectives, and recommendations. *Environ. Monit. Assess.* **2026**, *198*, 191. [CrossRef]
105. Tsui, T.-H.; Wong, J.W.C. A critical review: Emerging bioeconomy and waste-to-energy technologies for sustainable municipal solid waste management. *Waste Dispos. Sustain. Energy* **2019**, *1*, 151–167. [CrossRef]
106. Abdel-Shafy, H.I.; Mansour, M.S.M. Biogas production as affected by heavy metals in the anaerobic digestion of sludge. *Egypt. J. Pet.* **2014**, *23*, 409–417. [CrossRef]
107. de la Barrera, B.; Hooda, P.S. Greenhouse gas emissions of waste management processes and options: A case study. *Waste Manag. Res.* **2016**, *34*, 658–665. [CrossRef] [PubMed]
108. Turner, D.A.; Williams, I.D.; Kemp, S. Greenhouse gas emission factors for recycling of source-segregated waste materials. *Resour. Conserv. Recycl.* **2015**, *105*, 186–197. [CrossRef]
109. Fei, F.; Wen, Z.; Huang, S.; De Clercq, D. Mechanical biological treatment of municipal solid waste: Energy efficiency, environmental impact and economic feasibility analysis. *J. Clean. Prod.* **2018**, *178*, 731–739. [CrossRef]
110. Arafat, H.A.; Jijakli, K.; Ahsan, A. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. *J. Clean. Prod.* **2015**, *105*, 233–240. [CrossRef]
111. Zhang, J.; Kan, X.; Shen, Y.; Loh, K.-C.; Wang, C.-H.; Dai, Y.; Tong, Y.W. A hybrid biological and thermal waste-to-energy system with heat energy recovery and utilization for solid organic waste treatment. *Energy* **2018**, *152*, 214–222. [CrossRef]
112. Yaman, C. Investigation of greenhouse gas emissions and energy recovery potential from municipal solid waste management practices. *Environ. Dev.* **2020**, *33*, 100484. [CrossRef]

113. Srivastava, A.N.; Chakma, S. Lime sludge assisted anaerobic bioreactor landfilling of municipal solid waste for enhanced leachate stabilization and bioenergy yield. *Process Saf. Environ. Prot.* **2023**, *178*, 278–286. [CrossRef]
114. Rauch, R.; Kiros, Y.; Engvall, K.; Kantarelis, E.; Brito, P.; Nobre, C.; Santos, S.M.; Graefe, P.A. Hydrogen from waste gasification. *Hydrogen* **2024**, *5*, 70–101. [CrossRef]
115. Vamvuka, D.; Papanagiotou, N.; Ntounta-Marek, A. Valorization of Municipal Solid Wastes and Paper Mill Sludge Through Their Steam Co-Gasification for the Production of Energy Carriers Rich in H_2 and Lean in Greenhouse Gas Emissions. *Sustain. Chem. Eng.* **2025**, *6*, 99–113. [CrossRef]
116. Feng, S.; Zhang, G.; Yuan, D.; Li, Y.; Zhou, Y.; Lin, F. Co-pyrolysis of paper mill sludge and textile dyeing sludge with high calorific value solid waste: Pyrolysis kinetics, products distribution, and pollutants transformation. *Fuel* **2022**, *329*, 125433. [CrossRef]
117. Madhavaraj, M.; Karthikeyan, K. Assessing Waste-to-Energy Strategies for Municipal Solid Waste landfills in Chennai: A Case study using Energy-Economic-Environmental (3E) Approach. *Clean. Environ. Syst.* **2025**, *18*, 100321. [CrossRef]
118. Voukkali, I.; Papamichael, I.; Loizia, P.; Zorpas, A.A. Urbanization and solid waste production: Prospects and challenges. *Environ. Sci. Pollut. Res.* **2023**, *31*, 17678–17689. [CrossRef]
119. Rizwan, M.; Saif, Y.; Almansoori, A.; Elkamel, A. Optimal processing route for the utilization and conversion of municipal solid waste into energy and valuable products. *J. Clean. Prod.* **2018**, *174*, 857–867. [CrossRef]
120. Tapsuwan, S.; Moglia, M.; Po, M.; Walton, A.; Gardner, J.; Niazi, Z.; Uttam, A.; Schandl, H. Circular Economy in India: A Bayesian belief network analysis of household purchasing and disposal behaviour of plastics. *Resour. Conserv. Recycl.* **2025**, *220*, 108327. [CrossRef]
121. Moh, Y. Solid waste management transformation and future challenges of source separation and recycling practice in Malaysia. *Resour. Conserv. Recycl.* **2017**, *116*, 1–14. [CrossRef]
122. Kumar, R.; Thakur, A.K.; Gupta, L.R.; Gehlot, A.; Sikarwar, V.S. Advances in phase change materials and nanomaterials for applications in thermal energy storage. *Environ. Sci. Pollut. Res.* **2024**, *31*, 6649–6677. [CrossRef] [PubMed]
123. Garg, A.; Basu, S.; Malode, S.J.; Shetti, N.P. Potential organic waste materials for green hydrogen: A route for environmental sustainability. In *Green Hydrogen Economy for Environmental Sustainability. Volume 1: Fundamentals and Feedstocks*; 2024; pp. 249–286. [CrossRef]
124. Laverde-Albaracín, C.; González, J.F.G.; Nogales-Delgado, S.; Román, S.; Ledesma-Cano, B.; Peña-Banegas, D.; Ortiz, Y.; Gunsha-Morales, A. Biomass and Its Role in the Latin American Energy Mix: A Review of Biofuels and Bioelectricity Pathways Toward Sustainable Transitions. *Appl. Sci.* **2026**, *16*, 2246. [CrossRef]
125. Luo, T.; Hu, Y.; Zhang, M.; Jia, P.; Zhou, Y. Recent advances of sustainable and recyclable polymer materials from renewable resources. *Resour. Chem. Mater.* **2025**, *4*, 100085. [CrossRef]
126. Zhang, K.; Cui, J.; Zhou, Y.; Chen, A.J.Y.; Ouyang, C.; Palocz-Andresen, M.; Lou, Z. GHG emissions reduction patterns from waste sectors after forced source separation. *Process Saf. Environ. Prot.* **2023**, *180*, 443–450. [CrossRef]
127. Zhang, H.; Cui, J.; Liu, W.; Che, L.; Tian, W.; Lou, Z. Low-carbon competitiveness of cities in solid waste disposal systems: Spatial and temporal variations in greenhouse gas emissions in the Yangtze River Delta. *Waste Manag.* **2025**, *207*, 115100. [CrossRef]
128. Pramestyawati, T.N.; Afrianisa, R.D.; Thoyib, M.H.A. Greenhouse Gas Reduction Potential based on Waste Recovery Factor in Gading and Dukuh Setro Subdistrics. *J. IPTEK* **2023**, *27*, 79–88. [CrossRef]
129. Salah, W.A.; Abuhelwa, M.; Elnaggar, M.; Nassar, Y.F.; El-Khozondar, H.J.; Bashir, M.J.K. Assessment of waste to energy approaches to compensate for the shortage in energy supply in Gaza, Palestine. *Biofuels Bioprod. Biorefining.* **2025**, *19*, 2318–2332. [CrossRef]
130. Manesh, M.H.K.; Davadgaran, S.; Rabeti, S.A.M. Gasification potential of municipal solid waste in Iran: Application of life cycle assessment, risk analysis, and machine learning. *J. Clean. Prod.* **2024**, *434*, 140177. [CrossRef]
131. Luttenberger, L.R. Waste management challenges in transition to circular economy–case of Croatia. *J. Clean. Prod.* **2020**, *256*, 120495. [CrossRef]
132. Chen, S.; Huang, J.; Xiao, T.; Gao, J.; Bai, J.; Luo, W.; Dong, B. Carbon emissions under different domestic waste treatment modes induced by garbage classification: Case study in pilot communities in Shanghai, China. *Sci. Total Environ.* **2020**, *717*, 137193. [CrossRef] [PubMed]
133. Tanveer, M.; Khan, S.A.R.; Umar, M.; Yu, Z.; Sajid, M.J.; Haq, I.U. Waste management and green technology: Future trends in circular economy leading towards environmental sustainability. *Environ. Sci. Pollut. Res.* **2022**, *29*, 80161–80178. [CrossRef] [PubMed]
134. Azhagu, U.; Muniyappan, D.; Ramanathan, A. Advancements in plasma technology for circular waste management and green hydrogen production: A review. *J. Renew. Sustain. Energy* **2025**, *17*, 032701. [CrossRef]
135. Rautela, K.S.; Goyal, M.K.; Surampalli, R.Y. AI and Machine Learning for Optimizing Waste Management and Reducing Air Pollution. *J. Hazard. Toxic Radioact. Waste* **2025**, *29*, 4025014. [CrossRef]
136. Alouiz, I.; Aqil, M.; Dahbi, M.; Amarouch, M.Y.; Mazouzi, D. Performance of high-energy storage activated carbon derived from olive pomace biomass as an anode material for sustainable lithium-ion batteries. *Resour. Chem. Mater.* **2025**, *4*, 100086. [CrossRef]

137. Bellezoni, R.A.; Adeogun, A.P.; Paes, M.X.; de Oliveira, J.A.P. Tackling climate change through circular economy in cities. *J. Clean. Prod.* **2022**, *381*, 135126. [CrossRef]
138. Debnath, B.; Chowdhury, R.; Ghosh, S.K. Sustainability of metal recovery from E-waste. *Front. Environ. Sci. Eng.* **2018**, *12*, 2. [CrossRef]
139. Jensen, A.A.; Elkington, J.; Christiansen, K.; Hoffmann, L.; Møller, B.T.; Schmidt, A.; van Dijk, F. *Life Cycle Assessment (LCA)—A Guide to Approaches, Experiences and Information Sources*; European Environment Agency: Copenhagen, Denmark, 1997.
140. Balkau, F.; Bezama, A. Life cycle methodologies for building circular economy in cities and regions. *Waste Manag. Res.* **2019**, *37*, 765–766. [CrossRef]
141. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
142. Morseletto, P. Targets for a circular economy. *Resour. Conserv. Recycl.* **2020**, *153*, 104553. [CrossRef]
143. Okorie, O.; Salonitis, K.; Charnley, F.; Moreno, M.; Turner, C.A. Tiwari, Digitisation and the circular economy: A review of current research and future trends. *Energies* **2018**, *11*, 3009. [CrossRef]
144. Abad-Segura, E.; Batlles-delaFuente, A.; González-Zamar, M.-D.; Belmonte-Ureña, L.J. Implications for sustainability of the joint application of bioeconomy and circular economy: A worldwide trend study. *Sustainability* **2021**, *13*, 7182. [CrossRef]
145. Cao, Y.; Dhahad, H.A.; Alsharif, S.; Sharma, K.; El-Shafay, A.S.; Kh, T.I. Development of a MSW-fueled sustainable co-generation of hydrogen and electricity plant for a better environment comparing PEM and alkaline electrolyzers. *Sustain. Cities Soc.* **2022**, *81*, 103801. [CrossRef]
146. Kalyani, K.A.; Pandey, K.K. Waste to energy status in India: A short review. *Renew. Sustain. Energy Rev.* **2014**, *31*, 113–120. [CrossRef]
147. Iacovidou, E.; Hahladakis, J.N.; Purnell, P. A systems thinking approach to understanding the challenges of achieving the circular economy. *Environ. Sci. Pollut. Res.* **2020**, *28*, 24785–24806. [CrossRef] [PubMed]
148. Wright, C.Y.; Godfrey, L.; Armiento, G.; Haywood, L.K.; Inglesi-Lotz, R.; Lyne, K.; Schwerdtle, P.N. Circular economy and environmental health in low- and middle-income countries. *Glob. Health* **2019**, *15*, 65. [CrossRef]
149. Sikarwar, V.S.; Ji, G.; Zhao, M.; Wang, Y. Equilibrium modeling of sorption-enhanced cogasification of sewage sludge and wood for hydrogen-rich gas production with in situ carbon dioxide capture. *Ind. Eng. Chem. Res.* **2017**, *56*, 5993–6001. [CrossRef]
150. Sikarwar, V.S.; Pohořelý, M.; Meers, E.; Skoblia, S.; Moško, J.; Jeremiáš, M. Potential of coupling anaerobic digestion with thermochemical technologies for waste valorization. *Fuel* **2021**, *294*, 120533. [CrossRef]
151. Padmanabhan, S.; Giridharan, K.; Stalin, B.; Kumaran, S.; Kavimani, V.; Nagaprasad, N.; Jule, L.T.; Krishnaraj, R. Energy recovery of waste plastics into diesel fuel with ethanol and ethoxy ethyl acetate additives on circular economy strategy. *Sci. Rep.* **2022**, *12*, 5330. [CrossRef]
152. Berechet, M.; Mirel, I.; Staniloiu, C.; Fischer, K. Carbon footprint of waste management in romania in the context of circular economy. *Environ. Eng. Manag. J.* **2019**, *18*, 1289–1295. [CrossRef]
153. Sikarwar, V.S.; Pfeifer, C.; Ronsse, F.; Pohořelý, M.; Meers, E.; Kaviti, A.K.; Jeremiáš, M. Progress in in-situ CO_2-sorption for enhanced hydrogen production. *Prog. Energy Combust. Sci.* **2022**, *91*, 101008. [CrossRef]
154. Sikarwar, V.S.; Peela, N.R.; Vuppaladadiyam, A.K.; Ferreira, N.L.; Mašláni, A.; Tomar, R.; Pohořelý, M.; Meers, E.; Jeremiáš, M. Thermal plasma gasification of organic waste stream coupled with CO_2-sorption enhanced reforming employing different sorbents for enhanced hydrogen production. *RSC Adv.* **2022**, *12*, 6122–6132. [CrossRef]
155. Moško, J.; Jeremiáš, M.; Skoblia, S.; Beňo, Z.; Sikarwar, V.S.; Hušek, M.; Wang, H.; Pohořelý, M. Residual moisture in the sewage sludge feed significantly affects the pyrolysis process: Simulation of continuous process in a batch reactor. *J. Anal. Appl. Pyrolysis* **2022**, *161*, 105387. [CrossRef]
156. Mašláni, A.; Hlína, M.; Hrabovský, M.; Křenek, P.; Sikarwar, V.S.; Fathi, J.; Raman, S.; Skoblia, S.; Jankovský, O.; Jiříčková, A.; et al. Impact of natural gas composition on steam thermal plasma assisted pyrolysis for hydrogen and solid carbon production. *Energy Convers. Manag.* **2023**, *297*, 117748. [CrossRef]
157. Sikarwar, V.S.; Hrabovský, M.; Van Oost, G.; Pohořelý, M.; Jeremiáš, M. Progress in waste utilization via thermal plasma. *Prog. Energy Combust. Sci.* **2020**, *81*, 100873. [CrossRef]
158. Sikarwar, V.S.; Reichert, A.; Pohorely, M.; Meers, E.; Ferreira, N.L.; Jeremias, M. Equilibrium modeling of thermal plasma assisted co-valorization of difficult waste streams for syngas production. *Sustain. Energy Fuels* **2021**, *5*, 4650–4660. [CrossRef]
159. Srivastava, A.N.; Jeremias, M.; Sikarwar, V.S. Gasification of Sewage Sludge for Hydrogen Production. In *Hydrogen Production from Renewable Resources and Wastes*; CRC Press: Boca Raton, FL, USA, 2024; pp. 158–176.
160. Sikarwar, V.S.; Mašláni, A.; Hlína, M.; Fathi, J.; Mates, T.; Pohořelý, M.; Meers, E.; Šyc, M.; Jeremiáš, M. Thermal plasma assisted pyrolysis and gasification of RDF by utilizing sequestered CO_2 as gasifying agent. *J. CO_2 Util.* **2022**, *66*, 102275. [CrossRef]
161. Theuerl, S.; Herrmann, C.; Heiermann, M.; Grundmann, P.; Landwehr, N.; Kreidenweis, U.; Prochnow, A. The future agricultural biogas plant in Germany: A vision. *Energies* **2019**, *12*, 396. [CrossRef]

162. Singh, P.; Kalamdhad, A.S. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. *Sustain. Energy Technol. Assess.* **2022**, *54*, 102843. [CrossRef]
163. Ghosh, P.; Shah, G.; Chandra, R.; Sahota, S.; Kumar, H.; Vijay, V.K.; Thakur, I.S. Assessment of methane emissions and energy recovery potential from the municipal solid waste landfills of Delhi, India. *Bioresour. Technol.* **2019**, *272*, 611–615. [CrossRef]
164. Mavridis, S.; Voudrias, E.A. Using biogas from municipal solid waste for energy production: Comparison between anaerobic digestion and sanitary landfilling. *Energy Convers. Manag.* **2021**, *247*, 114613. [CrossRef]
165. Datta, M.; Somani, M.; Ramana, G.V.; Sreekrishnan, T.R. Feasibility of re-using soil-like material obtained from mining of old MSW dumps as an earth-fill and as compost. *Process Saf. Environ. Prot.* **2021**, *147*, 477–487. [CrossRef]
166. Fernández-Delgado, M.; del Amo-Mateos, E.; Lucas, S.; García-Cubero, M.T.; Coca, M. Liquid fertilizer production from organic waste by conventional and microwave-assisted extraction technologies: Techno-economic and environmental assessment. *Sci. Total. Environ.* **2022**, *806*, 150904. [CrossRef]
167. Yap, C.K.; Al-Mutairi, K.A. A conceptual model relationship between Industry 4.0—Food-agriculture nexus and agroecosystem: A literature review and knowledge gaps. *Foods* **2024**, *13*, 150. [CrossRef]
168. Ortiz-de-Montellano, C.G.-S.; Samani, P.; van der Meer, Y. How can the circular economy support the advancement of the Sustainable Development Goals (SDGs)? A comprehensive analysis. *Sustain. Prod. Consum.* **2023**, *40*, 352–362. [CrossRef]
169. Kowalski, Z.; Kulczycka, J.; Makara, A.; Mondello, G.; Salomone, R. Industrial symbiosis for sustainable management of meat waste: The case of Śmiłowo Eco-Industrial Park, Poland. *Int. J. Environ. Res. Public Health* **2023**, *20*, 5162. [CrossRef]
170. McCarthy, A.; Dellink, R.; Bibas, R. *The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches*; OECD: Paris, France, 2018.
171. Mulvaney, D.; Richards, R.M.; Bazilian, M.D.; Hensley, E.; Clough, G.; Sridhar, S. Progress towards a circular economy in materials to decarbonize electricity and mobility. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110604. [CrossRef]
172. Hopkinson, P.; Charnley, F.; Pencheon, D.; Dawson, T.; Eatherley, D.; Burton, K.; Gopfert, A. *Accelerating the Transition Towards a Net Zero NHS: Delivering a Sustainable and Resilient UK Healthcare Sector*; University of Exeter: Exeter, UK, 2022.
173. Nath, S.; Pillai, A.A.; Ram, A.; Gayathri, A.N.; Viswanath, N.; Tanjeri, P.; Anuradha, R.; Arulprasad, R. Quantitative analysis to identify circular economy concepts incorporated in Indian policy documents regulating waste management by the Indian Healthcare sector. *Resour. Conserv. Recycl.* **2025**, *214*, 108037. [CrossRef]
174. Srivastava, A.N.; Chakma, S. Bioavailability Reduction of Heavy Metals through Dual Mode Anaerobic Co-landfilling of Municipal Solid Waste and Industrial Organic Sludge. *Chem. Eng. J.* **2022**, *439*, 135725. [CrossRef]
175. Sverko Grdic, Z.; Krstinic Nizic, M.; Rudan, E. Circular economy concept in the context of economic development in EU countries. *Sustainability* **2020**, *12*, 3060. [CrossRef]
176. Pavolová, H.; Lacko, R.; Hajduová, Z.; Šimková, Z.; Rovňák, M. The circular model in disposal with municipal waste. A case study of Slovakia. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1839. [CrossRef]
177. Sahajwalla, V.; Hossain, R. Rethinking circular economy for electronics, energy storage, and solar photovoltaics with long product life cycles. *MRS Bull.* **2023**, *48*, 375–385. [CrossRef]
178. Srivastava, A.N.; Sikarwar, V.S.; Bisen, D.; Fathi, J.; Maslani, A.; Lopez Nino, B.N.; Barmavatu, P.; Kaviti, A.K.; Pohořelý, M.; Buryi, M. E-Waste Unplugged: Reviewing Impacts, Valorization Strategies and Regulatory Frontiers for Efficient E-Waste Management. *Processes* **2025**, *13*, 2014. [CrossRef]
179. European Commission. *A New Circular Economy Action Plan, For a Cleaner and More Competitive Europe*; European Commission: Brussels, Belgium, 2020.
180. Gharfalkar, M.; Court, R.; Campbell, C.; Ali, Z.; Hillier, G. Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Manag.* **2015**, *39*, 305–313. [CrossRef]
181. Circular Economy. *Sectoral Implementation of Nationally Determined Contributions (NDCs)*; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ): Bonn, Germany, 2017.
182. Bayar, Y.; Gavriletea, M.D.; Sauer, S.; Paun, D. Impact of municipal waste recycling and renewable energy consumption on CO_2 emissions across the European Union (EU) member countries. *Sustainability* **2021**, *13*, 656. [CrossRef]
183. Myrin, E.S.; Börjesson, P.; Ericsson, K. A case study on closed-loop recycling of co-polyester plates—Assessment of material quality and life-cycle energy and greenhouse gas performance. *Clean. Environ. Syst.* **2022**, *6*, 100091. [CrossRef]
184. Lemaire, A.; Limbourg, S. How can food loss and waste management achieve sustainable development goals? *J. Clean. Prod.* **2019**, *234*, 1221–1234. [CrossRef]
185. Pivato, A.; Girotto, F.; Megido, L.; Raga, R. Estimation of global warming emissions in waste incineration and landfilling: An environmental forensic case study. *Environ. Forensics* **2018**, *19*, 253–264. [CrossRef]
186. Liu, D.; Wang, S.; Xue, R.; Gao, G.; Zhang, R. Life cycle assessment of environmental impact on municipal solid waste incineration power generation. *Environ. Sci. Pollut. Res.* **2021**, *28*, 65435–65446. [CrossRef]
187. Tang, Y.; Dong, J.; Li, G.; Zheng, Y.; Chi, Y.; Nzihou, A.; Weiss-Hortala, E.; Ye, C. Environmental and exergetic life cycle assessment of incineration- and gasification-based waste to energy systems in China. *Energy* **2020**, *205*, 118002. [CrossRef]

188. Das, S.; Liang, C.; Dunn, J.B. Plastics to fuel or plastics: Life cycle assessment-based evaluation of different options for pyrolysis at end-of-life. *Waste Manag.* **2022**, *153*, 81–88. [CrossRef]
189. Rehl, T.; Lansche, J.; Müller, J. Life cycle assessment of energy generation from biogas—Attributional vs. consequential approach. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3766–3775. [CrossRef]
190. De Mattos, C.A.; De Albuquerque, T.L.M. Enabling factors and strategies for the transition toward a circular economy (CE). *Sustainability* **2018**, *10*, 4628. [CrossRef]
191. Silva-Ávila, P.; Hernández, J.R.; Barra, R.O. Knowledge Alliances for Global Change Adaptation: A Relational Approach Based on Traditional Ecological Knowledge, Territorial Management, and Community Practices in the Chilean Context. *Sustainability* **2025**, *17*, 3653. [CrossRef]
192. Kaza, S.; Yao, L.C.; Bhada-Tata, P.; Van Woerden, F.; Levine, D. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; World Bank: Washington, DC, USA, 2018. [CrossRef]
193. Samuel, F.U.; Oluwoye, J. Production of Biofuel from Pork Fat. In *Good Practices and Principles in Pig Farming*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 141–169.
194. Oshilalu, A.Z. Sustainability meets scalability: Transforming energy infrastructure projects into economic catalysts through supply chain innovation. *Int. J. Res. Publ. Rev.* **2024**, *5*, 762–779. [CrossRef]
195. Boxall, N.J.; Bolton, M.; Navarro, D.A.; Joll, C.A.; Heitz, A.; Niven, R.K.; Wong, B.B.; Williams, M.; Davis, G.B. Understanding how chemical risk can be managed in a circular economy. *Resour. Conserv. Recycl.* **2026**, *225*, 108600. [CrossRef]
196. Capstick, S.; Lorenzoni, I.; Corner, A.; Whitmarsh, L. Prospects for radical emissions reduction through behavior and lifestyle change. *Carbon Manag.* **2014**, *5*, 429–445. [CrossRef]
197. Magalar, L.; Verdolini, E.; Szklo, A. Unlocking circular economy policies in integrated assessment models. *Resour. Conserv. Recycl.* **2026**, *225*, 108614. [CrossRef]
198. McLarty, D.; Davis, N.; Gellers, J.; Nasrollahi, N.; Altenbernd, E. Sisters in sustainability: Municipal partnerships for social, environmental, and economic growth. *Sustain. Sci.* **2014**, *9*, 277–292. [CrossRef]
199. Domenech, T.; Bahn-Walkowiak, B. Transition towards a resource efficient circular economy in Europe: Policy lessons from the EU and the member states. *Ecol. Econ.* **2019**, *155*, 7–19. [CrossRef]
200. Kandpal, V.; Jaswal, A.; Santibanez Gonzalez, E.D.R.; Agarwal, N. Policy framework for sustainable energy transition and the circular economy. In *Sustainable Energy Transition: Circular Economy and Sustainable Financing for Environmental, Social and Governance (ESG) Practices*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 217–238.
201. Aparcana, S. Approaches to formalization of the informal waste sector into municipal solid waste management systems in low- and middle-income countries: Review of barriers and success factors. *Waste Manag.* **2017**, *61*, 593–607. [CrossRef] [PubMed]
202. Amoush, T.; Jum'a, L. The impact of industry 4.0 practices on sustainable performance in Jordan's retail sector: The moderating role of environmental dynamism. *Logistics* **2025**, *9*, 93. [CrossRef]
203. Kulakovskaya, A.; Knoeri, C.; Radke, F.; Blum, N.U. Measuring the economic impacts of a circular economy: An evaluation of indicators. *Circ. Econ. Sustain.* **2022**, *3*, 657–692. [CrossRef] [PubMed]
204. Chepeliev, M.; Aguiar, A.; Farole, T.; Liverani, A.; van der Mensbrugghe, D. Circular economy transition in Europe requires ambitious policies beyond climate mitigation. *Resour. Conserv. Recycl.* **2026**, *225*, 108591. [CrossRef]
205. Cervantes Puma, G.C.; Salles, A.; Bragança, L. Nexus between urban circular economies and sustainable development goals: A systematic literature review. *Sustainability* **2024**, *16*, 2500. [CrossRef]
206. Mwape, M.C.; Parmar, A.; Roman, F.; Emmambux, N.M.; Azouma, Y.O.; Hensel, O. Life cycle sustainability assessment of staple food processing: A double and dynamic materiality approach. *Sustain. Prod. Consum.* **2025**, *56*, 343–363. [CrossRef]
207. Masouleh, A.F. *Earthmate: Rethink, Revive, Sustain: A Bold Blueprint for a Greener Tomorrow*; Springer Nature: Berlin/Heidelberg, Germany, 2025.
208. Jacobs, C.; Soulliere, K.; Sawyer-Beaulieu, S.; Sabzwari, A.; Tam, E. Challenges to the circular economy: Recovering wastes from simple versus complex products. *Sustainability* **2022**, *14*, 2576. [CrossRef]
209. Lingaitiene, O.; Burinskiene, A. Development of trade in recyclable raw materials: Transition to a circular economy. *Economies* **2024**, *12*, 48. [CrossRef]
210. Cheshmehzangi, A. Everyday Circularity: Informal Labour and the SWaCH Model in Pune, India. In *Resourceful Urbanism: Designing Regenerative Cities Through Adaptive Reuse and Circular Innovation*; Springer: Berlin/Heidelberg, Germany, 2025; pp. 91–105.
211. Dias, S.; Samson, M. *Informal Economy Monitoring Study Sector Report: Waste Pickers*; WIEGO: Cambridge, MA, USA, 2016.
212. Klimecka-Tatar, D.; Kapustka, K. The Role of Artificial Intelligence in Circular Economy Strategies: Predictive Analysis for SMEs. *Manag. Syst. Prod. Eng.* **2025**, *33*, 212–219. [CrossRef]
213. Aragaw, T.T.; Chakma, S. Artificial Neural Network Model for Prediction of Methane Fraction in Landfill Gas from Pretreated Waste in Bioreactor Landfills. In *Integrated Approaches Towards Solid Waste Management*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 33–49.

214. Lakhouit, A. Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling. *Results Eng.* **2025**, *25*, 104018. [CrossRef]
215. Sharma, S.N.; Lodhi, A.S.; Dehalwar, K.; Jaiswal, A. Life Cycle Assessment (LCA) of Recycled & Secondary Materials in the Construction of Roads. In *Proceedings of the IOP Conference Series: Earth and Environmental Science, Jaipur, India, 12 August 2023*; IOP Publishing: Bristol, UK, 2024; p. 12102.
216. Mancini, G.; Luciano, A.; Bolzonella, D.; Fatone, F.; Viotti, P.; Fino, D. A water-waste-energy nexus approach to bridge the sustainability gap in landfill-based waste management regions. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110441. [CrossRef]
217. Wang, C.; Qin, J.; Qu, C.; Ran, X.; Liu, C.; Chen, B. A smart municipal waste management system based on deep-learning and Internet of Things. *Waste Manag.* **2021**, *135*, 20–29. [CrossRef]
218. Gupta, P.K.; Shree, V.; Hiremath, L.; Rajendran, S. The use of modern technology in smart waste management and recycling: Artificial intelligence and machine learning. In *Recent Advances in Computational Intelligence*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 173–188.
219. Anitha, R.; Parthiban, A. AI-IoT-graph synergy for smart waste management: A scalable framework for predictive, resilient, and sustainable urban systems. *Front. Sustain.* **2025**, *6*, 1675021. [CrossRef]
220. Anagnostopoulos, T.; Zaslavsy, A.; Medvedev, A.; Khoruzhnicov, S. Top–k query based dynamic scheduling for IoT-enabled smart city waste collection. In *Proceedings of the 2015 16th IEEE International Conference on Mobile Data Management, Pittsburgh, PA, USA, 15–18 June 2015*; IEEE: New York, NY, USA, 2015; pp. 50–55.
221. White, G.; Cabrera, C.; Palade, A.; Li, F.; Clarke, S. WasteNet: Waste classification at the edge for smart bins. *arXiv* **2020**, arXiv:2006.05873. [CrossRef]
222. Nafiz, M.S.; Das, S.S.; Morol, M.K.; Al Juabir, A.; Nandi, D. Convowaste: An automatic waste segregation machine using deep learning. In *Proceedings of the2023 3rd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST), Dhaka, Bangladesh, 7–8 January 2023*; IEEE: New York, NY, USA, 2023; pp. 181–186.
223. Bhattacharjee, T.; Bhave, S. Application of AI-Enabled Computer Vision Technology for Segregation of Industrial Plastic Wastes. In *Agroindustrial Waste Management and Natural Resources Conservation*; Apple Academic Press: Palm Bay, FL, USA, 2025; pp. 233–269.
224. Jin, S.; Yang, Z.; Królczykg, G.; Liu, X.; Gardoni, P.; Li, Z. Garbage detection and classification using a new deep learning-based machine vision system as a tool for sustainable waste recycling. *Waste Manag.* **2023**, *162*, 123–130. [CrossRef] [PubMed]
225. Cesetti, M.; Nicolosi, P. Waste processing: New near infrared technologies for material identification and selection. *J. Instrum.* **2016**, *11*, C09002. [CrossRef]
226. Lopez-Garcia, P.; Barrenetxea, X.; García-Arrieta, S.; Sedano, I.; Palenzuela, L.; Usatorre, L. Compounding process optimization for recycled materials using machine learning algorithms. *Procedia CIRP* **2022**, *105*, 237–242. [CrossRef]
227. Chang, C.; Di Maio, F.; Bheemireddy, R.; Posthoorn, P.; Gebremariam, A.T.; Rem, P. Rapid quality control for recycled coarse aggregates (RCA) streams: Multi-sensor integration for advanced contaminant detection. *Comput. Ind.* **2024**, *164*, 104196. [CrossRef]
228. Rastogi, S.; Sethi, P.; Pandey, H.; Panwar, N.; Yadav, P.; Madan, A. The Role of Robotics and Automated Systems in Refining Waste Separation Processes. In *AI Technologies for Enhancing Recycling Processes*; IGI Global Scientific Publishing: Hershey, PA, USA, 2025; pp. 441–490.
229. Adewuyi, A.Y.; Adebayo, K.B.; Adebayo, D.; Kalinzi, J.M.; Ugiagbe, U.O.; Ogunruku, O.O.; Samson, O.A.; Oladele, O.R.; Adeniyi, S.A. Application of big data analytics to forecast future waste trends and inform sustainable planning. *World J. Adv. Res. Rev.* **2024**, *23*, 2469–2479. [CrossRef]
230. KVasudevan, K. AI-driven solutions for real-time waste monitoring and management. *J. Recent Trends Comput. Sci. Eng.* **2024**, *12*, 11–20.
231. Alhathlaul, N.; Lakhouit, A.; Abdalla, G.M.T.; Alghamdi, A.; Shaban, M.; Alshahir, A.; Alshahr, S.; Alali, I.; Alshammari, F.M. Assessing Waste Management Using Machine Learning Forecasting for Sustainable Development Goal Driven. *Sustainability* **2025**, *17*, 8654. [CrossRef]
232. Pathan, M.S.; Richardson, E.; Galvan, E.; Mooney, P. The role of artificial intelligence within circular economy activities—A view from Ireland. *Sustainability* **2023**, *15*, 9451. [CrossRef]
233. Cagno, E.; Morioka, S.N.; Neri, A.; de Souza, E.L. Understanding how circular economy practices and digital technologies are adopted and interrelated: A broad empirical study in the manufacturing sector. *Resour. Conserv. Recycl.* **2025**, *216*, 108172. [CrossRef]
234. Zhang, Y.; Aldosky, A.J.; Goyal, V.; Meqdad, M.N.; Nutakki, T.U.K.; Alsenani, T.R.; Nguyen, V.N.; Dahari, M.; Nguyen, P.Q.P.; Ali, H.E. A machine learning study on a municipal solid waste-to-energy system for environmental sustainability in a multi-generation energy system for hydrogen production. *Process. Saf. Environ. Prot.* **2023**, *182*, 1171–1184. [CrossRef]
235. Swami, S.; Suthar, S.; Singh, R.; Thakur, A.K.; Gupta, L.R.; Sikarwar, V.S. Integration of anaerobic digestion with artificial intelligence to optimise biogas plant operation. *Environ. Dev. Sustain.* **2023**, *27*, 9773–9803. [CrossRef]

236. Bagheri, M.; Bazvand, A.; Ehteshami, M. Application of artificial intelligence for the management of landfill leachate penetration into groundwater, and assessment of its environmental impacts. *J. Clean. Prod.* **2017**, *149*, 784–796. [CrossRef]
237. Abunama, T.; Othman, F.; Ansari, M.; El-Shafie, A. Leachate generation rate modeling using artificial intelligence algorithms aided by input optimization method for an MSW landfill. *Environ. Sci. Pollut. Res.* **2019**, *26*, 3368–3381. [CrossRef] [PubMed]
238. Azadi, S.; Karimi-Jashni, A. Verifying the performance of artificial neural network and multiple linear regression in predicting the mean seasonal municipal solid waste generation rate: A case study of Fars province, Iran. *Waste Manag.* **2016**, *48*, 14–23. [CrossRef]
239. Nourani, V.; Baghanam, A.H.; Samadi, E.; Uzelaltinbulat, S. Predicting municipal solid waste generation using artificial intelligence: A hybrid approach of entropy analysis and SHAP for optimal feature selection. *Waste Manag.* **2025**, *205*, 115012. [CrossRef]
240. Giganti, P.; Falcone, P.M. Unveiling latent topics in the interplay of Circular Economy and Energy Transition: A Topic Modelling approach. *Resour. Conserv. Recycl.* **2025**, *219*, 108318. [CrossRef]
241. Majchrowska, S.; Mikołajczyk, A.; Ferlin, M.; Klawikowska, Z.; Plantykow, M.A.; Kwasigroch, A.; Majek, K. Deep learning-based waste detection in natural and urban environments. *Waste Manag.* **2022**, *138*, 274–284. [CrossRef]
242. Laksono, P.W.; Anisa, A.; Priyandari, Y. Deep learning implementation using convolutional neural network in inorganic packaging waste sorting. *Frankl. Open* **2024**, *8*, 100146. [CrossRef]
243. Shukhratov, I.; Pimenov, A.; Stepanov, A.; Mikhailova, N.; Baldycheva, A.; Somov, A. Optical detection of plastic waste through computer vision. *Intell. Syst. Appl.* **2024**, *22*, 200341. [CrossRef]
244. Mehrdad, S.M.; Abbasi, M.; Yeganeh, B.; Kamalan, H. Prediction of methane emission from landfills using machine learning models. *Environ. Prog. Sustain. Energy* **2021**, *40*, e13629. [CrossRef]
245. Olawade, D.B.; Fapohunda, O.; Wada, O.Z.; Usman, S.O.; Ige, A.O.; Ajisafe, O.; Oladapo, B.I. Smart waste management: A paradigm shift enabled by artificial intelligence. *Waste Manag. Bull.* **2024**, *2*, 244–263. [CrossRef]
246. Poudel, S.; Poudyal, P. Classification of waste materials using CNN based on transfer learning. In *Proceedings of the 14th Annual Meeting of the Forum for Information Retrieval Evaluation*; Association for Computing Machinery: New York, NY, USA, 2022; pp. 29–33.
247. Singh, D.; Tembhare, M.; Pundalik, K.; Dikshit, A.K.; Kumar, S. Machine learning based prediction of biogas generation from municipal solid waste: A data-driven approach. *Process Saf. Environ. Prot.* **2024**, *192*, 93–103. [CrossRef]
248. Lee, J.-S.; Shin, D.-C. Prediction of Waste Generation Using Machine Learning: A Regional Study in Korea. *Urban Sci.* **2025**, *9*, 297. [CrossRef]
249. Thakur, G.; Pal, A.; Mittal, N.; Yajid, M.S.A.; Gared, F. A significant exploration on meta-heuristic based approaches for optimization in the waste management route problems. *Sci. Rep.* **2024**, *14*, 14853. [CrossRef] [PubMed]
250. Cui, T.; Shi, Y.; Wang, J.; Ding, R.; Li, J.; Li, K. Practice of an improved many-objective route optimization algorithm in a multimodal transportation case under uncertain demand. *Complex Intell. Syst.* **2025**, *11*, 136. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.