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REVIEW

Progress of waste management in achieving UK's net-zero goal

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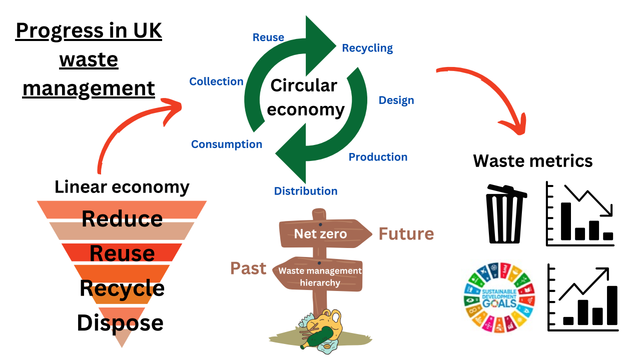
Abstract

The net-zero greenhouse gas (GHG) emissions strategy aims to avoid emissions from all economic sectors by 2050. Although the reduction of GHGs has been considered an urgent issue in all industrial divisions, there are still gaps in climate change mitigation strategies and policies in other sectors, such as waste, accounting for 3–5% of GHG emissions generation which are emitted from landfills, waste transport, waste treatment processes, and incinerators (Clark et al. in Nat Clim Chang 6:360–369, 2016; Masson-Delmotte V, Zhai AP, Connors C P, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., and Matthews TKM, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds) (2021) Climate Change 2021: the physical science basis. editor, contribution of working group I to the sixth assessment Report of the Intergovernmental Panel on Climate Change;). Waste management is a worldwide issue related to the circular economy. The share of the waste sector in the UK for GHG emissions generation is 3.7% in 2021, and landfills are responsible for 70% of the emissions (Rogelj et al. in Nat Clim Chang 591:365–368, 2021). Therefore, a new approach to waste management and disposal strategies is crucial. This paper reviews the key elements and challenges involved in waste management systems, specifically in the UK, including policy and legislation, infrastructure, and technological advancements. The review offers a clear summary of the application of circularity waste management strategies, focusing on the UK's goal to achieve the net-zero target. This review found that to reach the sustainable development goals (SDGs) and 2050 net-zero goals, the existing waste management hierarchy is no longer appropriate for the global and national setting. The metrics in waste management in the context of the circular economy should be aligned with the optimization of using resources, waste minimization, and increasing product life cycle by considering environmental impacts. Therefore, the circular model can be deployed instead of the hierarchy concepts.

Graphical abstract



Keywords Waste management · Net-zero 2050 · Circular economy · Environmental pollution · Sustainability development goals (SDGs) · Waste metrics

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Introduction

Background information

The release of approximately 2560 billion tons of CO_2 into the Earth's atmosphere between 1750 and 2019 is widely attributed to human activities and is considered the foremost contributor to climate change [1]. The current annual release of approximately 40 billion tons of CO_2 into the atmosphere continues to exacerbate the issue of rising global temperatures [2]. These findings underscore the pressing need for effective interventions to curb anthropogenic CO_2 emissions and mitigate climate change impacts.

To address the issue of rising global temperatures caused by greenhouse gas (GHG) emissions, the UK committed to the Paris Agreement in 2015. This commitment involves balancing GHG emissions and ensuring that global temperatures do not exceed a 2 °C increase by removing more GHG from the atmosphere than is emitted. This strategy, known as the net-zero target, entails achieving zero GHG emissions [3–5]. A global reduction of 1.4 billion tons of CO_2 annually is necessary to achieve the net-zero CO_2 emissions target by 2050 [6].

UK's carbon budget and 2050 net-zero target

The remaining carbon budget is the total amount of CO_2 that can be emitted to limit global warming. It involves reducing global CO_2 emissions to reach net-zero levels and stabilizing CO_2 concentrations in the atmosphere. The remaining global carbon budget from the beginning of 2020 to limit global warming to below 1.5 °C has been estimated to be between 420 and 570 billion tons of CO_2 based on the "Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6)" [2, 6, 7]. The annual CO_2 emissions worldwide were about 36.4 billion tons of CO_2 in 2021 [8]. China, the United States, and India were the world's largest CO_2 emitters in 2020, with 10.7, 4.7, and 2.4 billion tons, respectively [6, 9]. Hence, the remaining 420 billion tons of CO_2 from the carbon budget will be used by 2030 if CO_2 emissions remain unchanged.

In 2008, the UK's target was to reduce GHG emissions by 80% in 2050 compared to the 1990 level, which was 813 million tons (Mt) CO_2eq [10]. The UK's GHGs were 417.1 MtCO_2e in 2022, which was a 51.27% reduction compared to 1990 [11]. However, in light of the new net-zero carbon target, the UK government revised its goal to a 100% reduction in GHG emissions by 2050 [12]. The UK has implemented five-yearly carbon budget strategies to attain net-zero carbon emissions by 2050 [13]. There are six carbon budgets from 2008 until June 2021 [12]. In the sixth carbon budget, emissions from international aviation and shipping have been considered for the first time [14]. Table 1 details the status of each carbon budget amount and the status of meeting deadlines [15]. Based on the UK government's final statement reports for the first and second carbon budget periods, the UK successfully remained 36 MtCO_2e below the limitation level of 3018 MtCO_2e in the first carbon budget. In the second carbon budget, the UK achieved 384 MtCO_2e below the cap of 2782 MtCO_2e [12, 14]. To comply with the third carbon budget limit, the UK must reduce its net yearly emissions below 508.8 MtCO_2e [14]. Therefore, if the UK aims to keep the carbon budget at its baseline, a 20% annual reduction is required [16].

UK's net-zero emissions strategy aims to avoid emissions from all economic sectors by 2050 [17]. For the past twenty years, the UK's priorities in reducing GHG have been predominantly focused on curbing GHG generation by energy supply and transportation sectors. There are still gaps and opportunities in climate change mitigation strategies and policies in other industrial sectors such as building, agriculture, process industries, and waste [18]. Figure 1 shows the UK's industrial emissions by source in 2020. The transportation sector accounted for 25.7% of net GHG in the UK, followed by energy supply (20.4%), business (17.7%), residential (16.3%), and agriculture (11.2%). The remaining sectors, waste management, industrial processes, and the public sector, accounted for 8.6% [14].

Table 1 UK carbon budgets [15, 194]

Carbon budget	Time scaling	Carbon budget cap (MtCO_2e)	Reduction below 1990 levels	Status
CB1	2008–2012	3,018	25%	Done
CB2	2013–2017	2,782	31%	Done
CB3	2018–2022	2,544	37% by 2020	In progress (will be published in May 2024)
CB4	2023–2027	1,950	51% by 2025	–
CB5	2028–2032	1,725	57% by 2030	–
CB6	2033–2037	965	78% by 2035	–

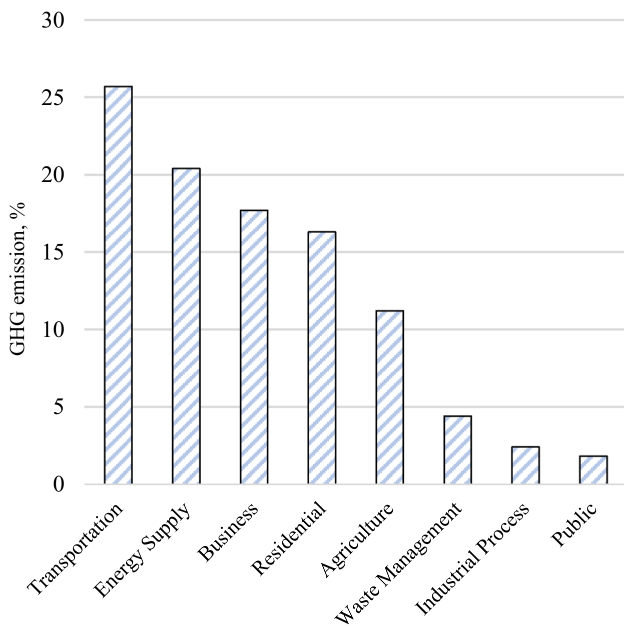


Fig. 1 UK GHG emissions by industrial sectors, 2020 [14]

Although the share of the waste contribution to national emissions is lower than other divisions, there are crucial matters that cover a range of environmental, economic, sustainability, and social issues related to decarbonizing the waste sector. Waste streams commonly contain valuable resources, including metals, plastics, organic compounds, etc. [19], so resource conservation from waste streams is essential. Natural resources would be saved by preventing these materials from being disposed of in landfills or burned in incinerators [20]. Moreover, soil, air, and water pollution can result from improper waste management. Effective waste stream management can reduce these detrimental environmental effects and positively impact the environment [21].

An added benefit is that waste-to-energy technology could turn particular wastes into electricity or heat, helping to increase energy output and lowering the need for fossil fuels. Besides, effective waste management lessens GHG emissions from incineration and landfill decomposition [22, 23]. In other words, proper waste management can result in lower disposal costs, energy production and economic benefits from selling recycled waste [24]. Waste production and its adverse environmental effects can be minimized by promoting a circular economy, which includes reusing, repairing, remanufacturing, and recycling materials [25, 26]. In addition, by recycling and reusing materials from waste streams, extended product life will be attainable [27], which will drop the demand for new production. By adequately handling waste streams, the need to import raw resources for nations will be lessened, boosting national resource security [28].

Proper waste management limits environmental risks through the secure disposal of waste, improving ecological protection and the overall quality of life and well-being in societies [29]. In this regard, technological advancements for more effective waste management drive technological innovations in waste management, resulting in more sustainable solutions [20, 30]. To mitigate climate change, reliable and sustainable waste management systems diminish GHG emissions significantly [23]. Consequently, addressing waste streams is vital for decreasing environmental impact, protecting resources, boosting economic growth, and promoting a sustainable and responsible approach to waste management.

Solid waste generation has rapidly increased with the growing global population, rapid urbanization, and economic growth worldwide. By 2050, the number of waste products is expected to exceed population growth by over double [31, 32]. As a result, the share of global GHG emissions generated from solid waste will be 5% [31, 33], and improvement in this sector affects GHG reduction, community health, welfare, productivity, and cleanliness [31].

Even though there has been a 70% reduction in GHG emissions in the UK's waste sector over the last three decades [14] by improvements in managing and controlling landfill site operations, applying novel carbon capture technologies in energy recovery facilities, and following the EU Waste Framework Directive (WFD) and policies, there are still further potential actions and improvements in the UK's waste management strategy [13]. In other words, more emission reductions in this sector are viable, enabling the UK to reach its carbon budget by reducing the reliance on emission reduction targets in different economic sectors and accomplishing the government's long-term goal of becoming a zero-avoidable waste economy by 2050.

Aim of this review

The review aims to examine the main challenges and the current status of UK waste management systems and how the UK's 2050 net-zero goals can be reached by improved circularity.

Waste management and circularity terms

Waste and waste management strategies

Solid waste (SW) is a heterogeneous mixture of waste materials generated from various sources, such as households, industries, businesses, farms, and buildings [22]. SW generation has rapidly increased with the growing global population, rapid urbanization, and economic growth worldwide.

Global waste per person is 0.74 kg daily, varying by income, region, and population growth [31]. Due to natural resource consumption and lifestyle changes, SW will increase from 2.01 in 2016 to 3.4 billion tons annually by 2050 [22, 31]. Figure 2 depicts the influence of income level circumstances on waste generation worldwide. It proves that high-income nations generate more waste than low-income due to various consumption patterns, accessibility of products, affordability and lifestyles in lower-income settings. The quality of waste is influenced by numerous factors, including collection methods, seasonal patterns, and recycling practices [34]. According to Fig. 3 [13, 16], food, paper and plastic waste ranks among the top global waste generation. Developed countries with high income levels generate more plastics and paper waste while developing countries produce more organic waste, including food and agricultural waste [35].

Almost 40% of global waste is buried in landfills, 19% is recycled or composted, 11% is processed through advanced incineration and energy recovery methods, and 33% is littered into the environment [31, 36]. As a result, SW generation leads to severe air, land, and water pollution. For instance, the leakage of liquid leachate from landfills contains heavy metals and toxic components which pollute surface water and soil [30].

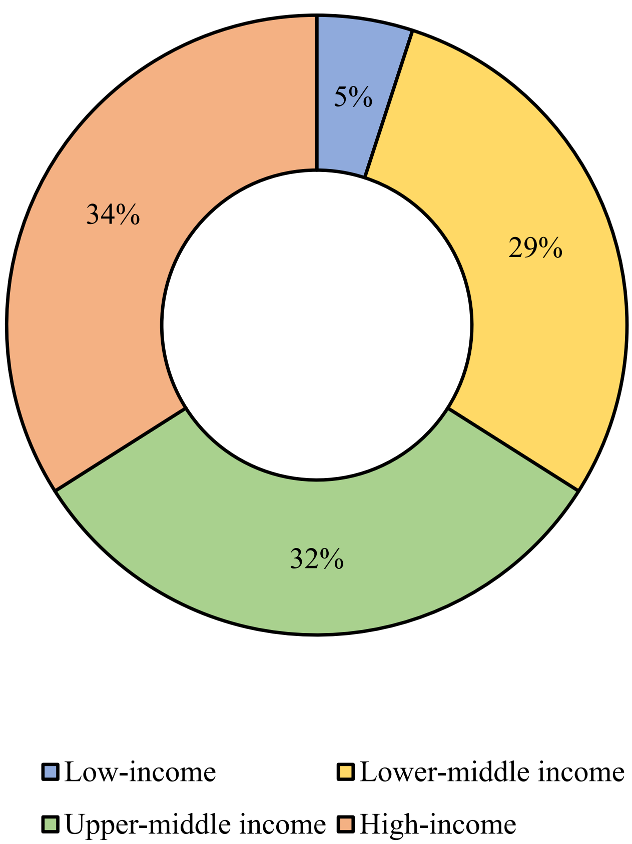


Fig. 2 Global share of waste generation by income level [31]

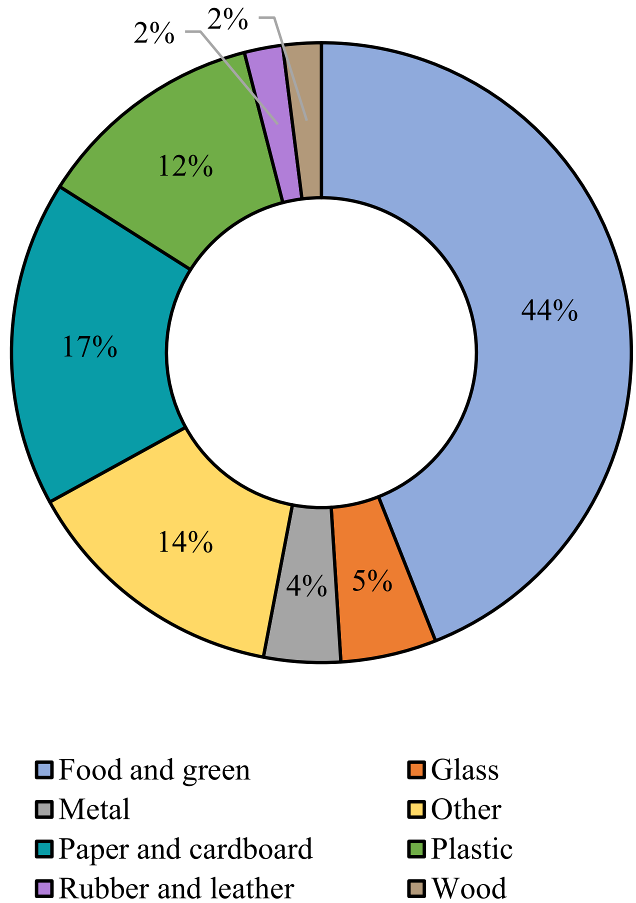


Fig. 3 Global waste composition [31]

Efforts to improve waste management by reducing landfill emissions and increasing energy recovery through recycling can mitigate global GHG emissions by approximately 15% [18, 22]. Studies in different industries address how to minimize the effects of environmental, economic, health, and risk issues related to the generated volume of SW sent to landfills and waste disposal sites worldwide [37–39]. They recommend a combined SW network for sorting, collecting, and transferring to disposal sites based on waste types and increasing waste treatment capacities, particularly in recycling infrastructures. Moreover, they suggested that systematic policies can tackle waste management issues in various industrial sectors.

The definition of waste management in the "Waste Framework Directive (WFD) 2008/98/EC of the European Parliament and the Council" law of 2008 is "the collection, transport, recovery, and disposal of waste with the supervision of such operations and after-care of disposal sites as a dealer or broker" [40–42]. Based on each phase of the waste management system, research has been conducted on waste reduction, recycling, enhanced landfill gas recovery, composting, and energy recovery [18, 22, 43–45]. The WFD uses the term waste for any holder's material or objects to be discarded or required to be discarded [40, 46].

Energy recovery from SW is one of the main topics in developing waste management systems to tackle the environmental problems of disposal sites and improve incineration facilities. It is a practical option that covers the use or extraction of discarded waste materials for reuse, limits GHG emissions, and reduces the volume of disposed waste. In addition, solid wastes have a significant energy potential, and waste treatment processing and conversion technologies might be utilized to generate heat, gas, or electricity.

Two waste-to-energy processes based on SW's nature and quantities are favored. The thermal breakdown of waste materials produces energy through thermochemical conversions such as incineration, gasification, combustion, pyrolysis, carbonization, and mechanical extraction. The biochemical conversion process is based on the denaturation of waste material with the help of enzymes or microbes. Two important biochemical conversion processes are anaerobic digestion and fermentation. These techniques are widely used for SW with a high putrescible percentage and moisture content, boosting microbial activity.

In 2017, most European countries used incinerators to convert waste into energy, which is the most efficient approach to eliminating SW from landfills [22, 30, 47, 48]. The most common waste management systems reviewed in the literature are characterized in Table 2 [22, 30]. However, focusing just on energy recovery disregards other alternative approaches like recycling.

The waste management hierarchy is a key concept in WFD, playing a crucial role in promoting effective waste management practices. This hierarchy outlines a structured approach to prioritize various waste management strategies. The aim is to encourage waste reduction at its source, stimulate the re-utilization of materials, and emphasize recycling and recovery techniques over traditional disposal methods.

The WFD underscores the hierarchy's significance, recognizing its potential to limit environmental repercussions, conserve resources, and alleviate pressure on landfills. By endorsing this framework, the WFD underscores its dedication to fostering a circular economy, leading to a more sustainable approach to waste management. Article 4 of WFD's waste hierarchy consists of stages to manage and prevent waste (Fig. 4) [40–42]. The stages are arranged according to the circular economy strategy of increasing the value of existing resources in the prevention, reuse, and refurbishment phases. Furthermore, minimizing waste through recycling and conversion to new resources. This waste management hierarchy is valid for most materials. However, the waste hierarchy can be explicitly altered to

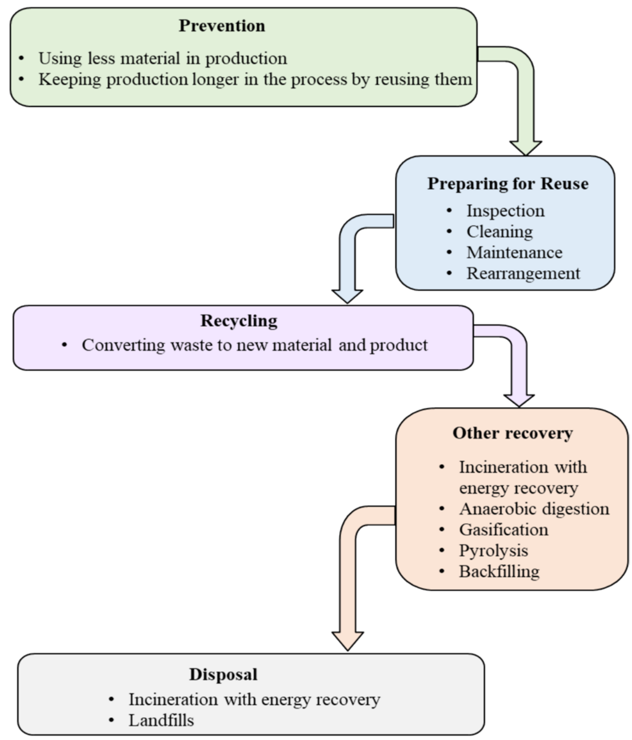


Fig. 4 The waste hierarchy [42]

Table 2 Main waste management systems [22, 30]

Conversion method	Main products	By-products	Toxic components	Operating temperature °C
Incineration	Heat, energy	Ash	Dioxins, heavy metals	400–1000
Gasification	CO, H_2, N_2, CH_4	Vitreous slag	Polyhalogenated organic compounds	550–900 (in air gasification), 1000–1600
Combustion	CO_2, H_2O	Ash	Polycyclic aromatic hydrocarbons	850–1200
Pyrolysis	CO_2, H_2, CH_4, Wax, tar, bio-oil	Char	Hydrogen cyanides, polyacrylonitriles	200–760
Anaerobic digestion	Biogas, CH_4, CO_2	Sludge/slurry	NH_3	30–60
Fermentation	Ethanol, CO_2	Bio-solids	NH_3	30–35
Carbonization	Hydro-char	Oils, Chemical, Rich process water	HCN, CO, NH_3	180–350
Mechanical extraction	Oil, particle board	Press residues	Phenolic compounds	140–185

reduce the environmental effects of waste materials like paper, food, garden waste, glass, and plastic [42].

Current frameworks of waste management hierarchies do not include specific environmental measures, indicators, or metrics. They prioritize specific actions on avoiding, minimizing, and restoring steps and pay less attention to quantitatively measuring specific environmental results from each step. This omission limits their effectiveness in achieving ecological and resource conservation or sustainability objectives. Therefore, additional tools and methodologies should be added to the waste management hierarchy to assess environmental impacts quantitatively and ensure accountability and effectiveness in reaching environmental goals related to each stage.

Several research investigations examined sustainable waste management models and analyzed the models regarding environmental performance, financial concerns, and material management [49–52]. Over the last two decades, the systems analysis methodology has been used to conduct waste management systems based on engineering models and assessment tools. Simulation, optimization, prediction, profit analysis, and integrated modeling systems have been discussed in systems engineering models. In addition, the contribution of data management systems, scenario selection, material flow analysis, life cycle assessment, risk assessment, socio-economic assessment, and decision support tools to waste management are considered in system assessment tools [53].

These studies reviewed the merits and limitations of various waste management models alone or combined with other assessment models and tools [30, 47, 52, 53]. GHG mitigation costs and potential elements influencing social, environmental, and economic issues from a system level cost perspective in various waste management systems were the outputs measured in these studies. They came to a conclusion with multifaceted models and cooperative methods for evaluating sustainability that may be used in policy decisions,however, they might not be transferable to other settings or regions with differing waste legislations.

The significant gaps found from these evaluations are related to data input and output to waste management systems due to growth in SW quantities and various qualities. Hence, efficient data collection is recommended for analyzing complex waste management systems. Moreover, most case studies have not focused on waste prevention strategies. Therefore, a new concept of zero waste management has been reviewed for suggestions to policymakers. At the same time, only a few research concentrated on zero-waste design, engineering, sustainable consumption, and assessment. To reach a feasible zero-waste philosophy, there are technical issues to implement for waste generators, waste collectors, and waste-to-resource converters [45, 54, 55].

Even though several studies have examined sustainable waste concepts and methods worldwide, universal monitoring and management of global waste to reach comprehensive global strategies are still limited. To develop a comprehensive and sustainable waste management system, concerns linked to prevailing waste management philosophies in various countries should be examined, environmental assessments should be made, and the capability of prospective waste recycling or reusing should be considered.

Therefore, to improve the hierarchy of waste minimization in achieving waste reduction and sustainability goals, the contribution of relevant metrics as quantitative and qualitative measures, which is the main gap in the waste hierarchy, should be considered. These metrics are categorized based on the prioritized levels shown in Fig. 4, including the rate of waste generation rate, rate of waste diversion, recycling rate, composting rate, efficiency of energy recovery processes, carbon emission reduction, financial savings, resource conservation indicators, environmental impact indicators, driving improvements in waste reduction strategies and circular economy.

Circular economy and waste management

Since natural resources on the Earth are limited, a sustainable way of using rare resources to gain economic growth, social welfare, and environmental protection is desirable [26]. However, despite global prosperity and wealth development through linear economic thinking up to the twentieth century, using finite resources and extracting raw materials in unsustainable methods led to massive waste and pollution [56–58]. In other words, instead of using the traditional linear economy notion, including “take, make, use, and dispose”, the new concept of circular economy (CE) approach based on reuse, resource efficiency, and closed-loop terms has emerged (Fig. 5). CE is vital in tackling climate change, environmental issues, worldwide population growth, lack of natural resources, and fossil feedstock shortage [56, 59].

The early work on a sustainable economy term was initiated in 1966, which proposed implementing a cyclical ecological system as a replacement for considering open systems (the linear economic models) in energy and material supplements [60]. The concept of a closed-loop, self-sustaining economic system was introduced in 1982 [61]. In 1989, the CE definition was announced for the first time, and in 1990, the work on the transition from “resource–products–pollution” thinking toward “resource–products–regenerated resources” in business models was developed [57, 62].

In the 1990s, the CE “Reduce, Reuse, and Recycle” principles resulted in green manufacturing focusing on reducing finite natural resource consumption and minimizing pollution, emissions, and waste during manufacturing [26].

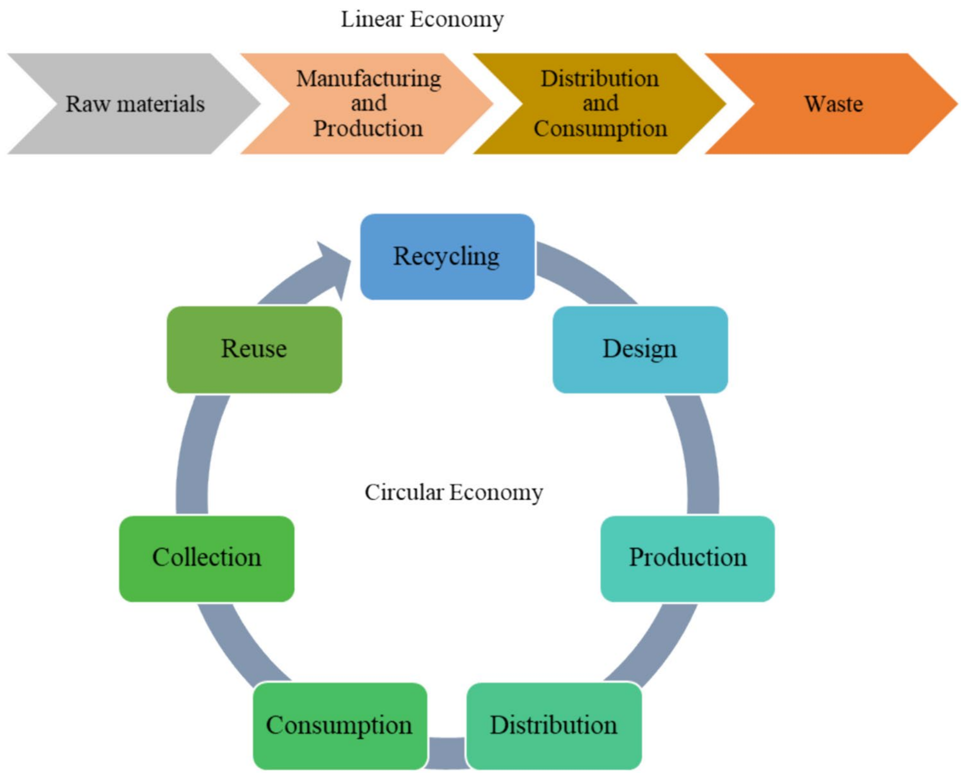


Fig. 5 Linear economy vs circular economy steps

Global corporations and enterprises have used closed-loop supply chains throughout the last decade to prevent turning large amounts of resources into waste or pollution [56]. Furthermore, some studies have been completed on using resources repeatedly to keep the maximum available quality of products and commodities in the economy [63–66]. They suggested the new term upcycling rather than recycling. They highlighted that rather than allowing resources, components, and products to depreciate, try to keep their high worth [63–66].

The CE concept focuses on collecting waste streams for reuse and recycling as a source of secondary resources. Applying CE in the product design process will optimize the lifetime while minimizing the environmental effect. The European Commission established a "European Union Action Plan for a Circular Economy" in 2015 [31] to create a global, low-carbon economy that is resource efficient and sustainable based [67]. This action plan consists of legislation for directives on waste, packaging waste, and landfills [68]. The European Union introduced a comprehensive strategy in 2018 to facilitate the Action Plan's execution and the EU's goal of a circular economy [31, 68, 69].

Through several approaches, the CE model can help the UK reach its net-zero goal by 2050 [70–72]. By applying the CE model, the demand for virgin resources [73] and waste production will be reduced by promoting the reuse, repair, and recycling of materials, which is correlated to lower GHG emissions linked to resource extraction, manufacture, and disposal [72, 74]. Circular methods also improve the life of materials, which drops the need for frequent replacements and, over time, lowers energy consumption and carbon emissions [75, 76]. In addition, developing renewable energy usage can be a shift to circular business models, which lowers emissions in the UK [77, 78].

Some studies show that keeping resources in use as long as possible, extracting maximum value, and minimizing waste in the packaging industry [79–81] and food supply chain can be the method of applying of the CE model based on policy statements issued by the UK government [82–84]. Likewise, aligning net-zero goals with CE approaches could reduce up to 50% of the UK's carbon emissions if applied to producing and using key materials like cement, steel, plastic, and aluminum [85–89]. This finding demonstrates the potential of CE approaches to contribute meaningfully to the UK's net-zero ambitions [85, 86]. The CE can decrease emissions, promote resource efficiency, and advance a sustainable future through government policies, industry practices, and a shift in societal consumption patterns in the UK.

Additionally, studies highlight the need to create long-lasting and items easy to disassemble, reducing the requirement for virgin materials and the related emissions connected with manufacture in terms of waste electrical and electronic equipment [90–93]. The outcomes reveal that only 17% of these wastes are recycled in the UK, and the rest are dumped in landfills without being disposed of effectively, leading to hazardous compounds contaminating the land, water, and air, threatening human health and the ecosystem [72, 94]. By implementing these concepts, the UK could switch from a system of massive waste generation in all sectors to a closed-loop strategy that maximizes resource utilization, reducing overall GHG emissions and aiding in the activity of net-zero aims.

In 2010, it was estimated that around 22% of the business sectors employed the UK CE practice. This metric has not been updated in the past decade. According to the 'Waste and Resources Action Programme' (WRAP) report, the circularity of the UK economy may climb to 27% by 2030, with a 30 million ton drop in annual material consumption [41, 95]. The concept of CE in business models by some companies across the UK has been applied recently,however, different attitudes toward CE have been shaped throughout the UK. The reason is that fundamental policy fields have been divided among several entities, and there is no unity in local authorities, governmental bodies, and statistics assigning policy. Therefore, each body has its strategy for applying, supporting, and measuring CE concepts [96].

As described earlier, a CE approach keeps materials and resources in the production supply chain. It extends their lifetime in the market to limit waste generation and ease the burden on finite natural resources demands for feedstock supply. Therefore, a sustainable waste management hierarchy aligned with CE notions in creating added value to waste, reducing carbon footprints, and increasing energy efficiency will be desirable to achieve the most significant environmental benefits and introduce valuable resources into the economy. To establish a sustainable waste management system, environmental and potential pollution assessment in different sustainable disposal techniques aligned with economic development should be regarded as a transition from a linear economy to a circular economy. The circular economy concept focuses on reusing and recycling waste streams as a source of secondary resources and keeping them in the production cycle to minimize the environmental impact of final waste treatment methods.

Most waste management studies have concentrated on multi-industrial supply chains from a growing economic efficiency point of view and suggested further production during recycling without considering sustainable infrastructures for environmental aspects such as releasing emissions [97]. This concept contributes to intensifying pollution in the environment [98]. Although the CE principle is a sustainable approach to producing products from waste materials, it requires management adaptation in the commercial and industrial sectors to minimize pollution [99]. However, there are substantial obstacles to waste management adoption in some firms and industries, summarized as follows [67, 97, 100–105]:

- The importance of waste reduction and its application are undervalued.
- Making a product from waste is challenging since it necessitates creative thinking and novel technologies.
- Collecting, sourcing, treating, and remanufacturing waste is a costly procedure.
- Due to the nature of the waste and waste quantities, recycling is a challenging process.
- Employee training and updated skills regarding new technologies need time and cost.
- Lack of sufficient investment and support from the government and stakeholders.
- Lack of customer acceptance of recycled products due to concerns about the quality of reused materials.

The initial studies on CE concentrated on working with closed-loop systems for materials and energy in advanced processes [26, 66, 67, 106, 107]. However, a significant gap existed between developing, designing, and optimizing technologies for industry practice and achieving CE fundamentals linked to commercial needs in the manufacturing supply chain. In addition, the impediment associated with converting waste into value from non-convertible waste is another challenging process [67, 104, 108–110]. Moreover, different CE approaches should be applied due to various waste hierarchy implementations and operational steps like collection, sorting, pre-treatment, reusing, recycling, composting, biological treatment, energy recovery, incineration, and landfills, leading to different potential measurements in waste statistics. As a result, there is a substantial gap between waste statistics and waste operations efficiency in each stage of the waste management hierarchy [25].

Most related works on CE in the UK are related to policy and the contribution of different sectors in decision-making scenarios for waste management principles. They suggested indicator tools to gain the optimum and uniting decisions agreed upon by all stakeholders [111].

Therefore, to obtain CE approaches in waste sectors, quantitative metrics to improve the hierarchy of waste minimization framework can be a novel framework of the hierarchy edition mentioned in Sect. 3.1. CE emphasizes practices including recycling, reusing, and remanufacturing to minimize waste and make the most of resources. These contributions are aligned with CE principles such as recyclability, material efficiency, waste diversion, energy efficiency, circular design, and energy efficiency. By contributing to enhancing associated metrics within the framework of CE techniques, increasing sustainability, waste reduction, and responsible resource management can be achieved.

UK waste overview

Waste generation by economic sectors in the UK is defined as construction and demolition and excavation (CD and E), commercial and industrial (C and I), waste from households, and hazardous waste [17], which are governed under Article 3 of WFD [40]. The UK statistics on waste [22] show that total waste generation in England has risen from 187 to 222 million tons from 2016 [17] until 2018 [112]. Table 3 illustrates that England's entire UK waste generation share is 84% of the UK's total waste generation [113]. The most significant portion of waste generation is related to CD and E, with a share of 62% of the total UK waste (Fig. 6) [113]. The highest waste material category in the UK in 2018 was 'mineral wastes' and 'soils', accounting for 80.4 million tons and 58.5 million tons, respectively,nearly two-thirds (63%) of total UK waste belongs to this waste [113].

The share of the waste sector in the fourth and fifth carbon budgets is projected to be about 3%. It is estimated that emissions from the waste management sector will decrease from 93 Mt CO_2e in the second budget to 55 Mt CO_2e in the fifth budget at the end of 2032, leading to total GHG emissions reduction to 6 and 9% for the fourth and fifth carbon budget respectively [13]. The waste management sector accounts for 4% of GHG emissions in the UK in 2020 [14] from waste disposal at landfill sites, incineration facilities, wastewater treatment, and biological treatment [13, 14]. The waste management sector's GHG emissions were reduced by 73% between 1990 and 2020. The reasons are improvements in landfilling standards, changes in the types of waste going to landfills (such as lowering the amount of food waste), and the use of landfill gas for electricity or heat generation [14].

In 2015, 67% of the sector's total emissions belonged to landfill sites [13]. It is reported that landfill sites were responsible for 14,446 tons of CO_2e in 2015, which is projected to increase to 17,821 tons of CO_2e by 2030. In this regard, waste reuse, recycling scenarios, and landfill taxes have been considered in the UK strategies to control emission production. As a result, CO_2e will be reduced to 801,105 tons by 2030 [30, 114]. Imposing a landfill tax in the UK is one of the significant actions to reduce waste volumes sent to landfill. This tax was introduced in 1996 following EU landfill directive regulation and considered £7 per ton of waste. It was increased to £102.10 per ton in 2023 [115, 116].

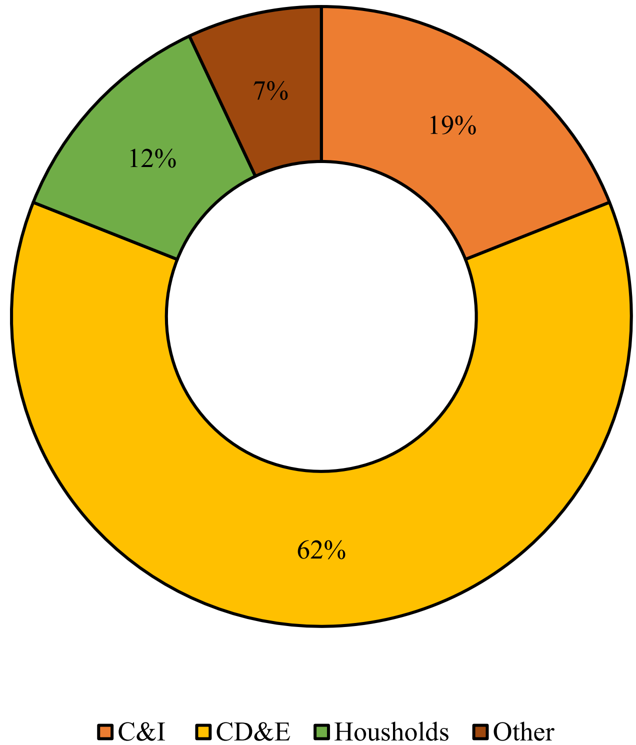


Fig. 6 Waste generation share by source, UK, 2018 [113]

In other words, implementing high landfill taxes has incentivized waste managers to adopt alternative waste disposal and management practices, such as recycling, composting, and waste-to-energy conversion, as more cost-effective alternatives. However, this approach might be prioritizing economic benefits beyond environmental effects, potentially leading to the adoption of waste management techniques that are advantageous commercially but may not always be the most environmentally friendly. For example, encouraging incinerators is advantageous for producing more energy and potentially decreasing landfill dependency, but GHGs and other pollutants will be escalated. The main obstacle here is ensuring the environmental effects of various waste management solutions to balance energy production and environmental protection

Table 3 Waste generation per sector (million tons) and % change, UK and England, 2016–2018 [113]

	Year	C and I	CD and E	Households	Other	Totals
UK	2016	39.8	136.2	27.3	15	218.3
	2018	42.6	137.8	26.4	15.4	222.2
	Change	7%	1.2%	− 3.3%	2.8%	1.8%
England	2016	32.1	120.3	22.8	9.5	184.6
	2018	36.1	119.4	22	9.7	187.3
	Change	12.4%	− 0.7%	− 3.2%	2.9%	1.4%

instead of just going with the simplest or most cost-effective option.

Treatment methods in the UK

The current waste treatment methods in the UK between 2016 and 2018 are presented in Fig. 7 [113]. In 2018, the UK's most common final waste treatment type was 'recycling and another recovery', accounting for 50.4%. The recovery of mineral wastes and soils from the construction, demolition, and excavation sectors accounts for roughly two-thirds of 'recycling and another recovery'. A landfill is the UK's second most used waste disposal method, accounting for 23.6% of total waste disposal in 2018 [112].

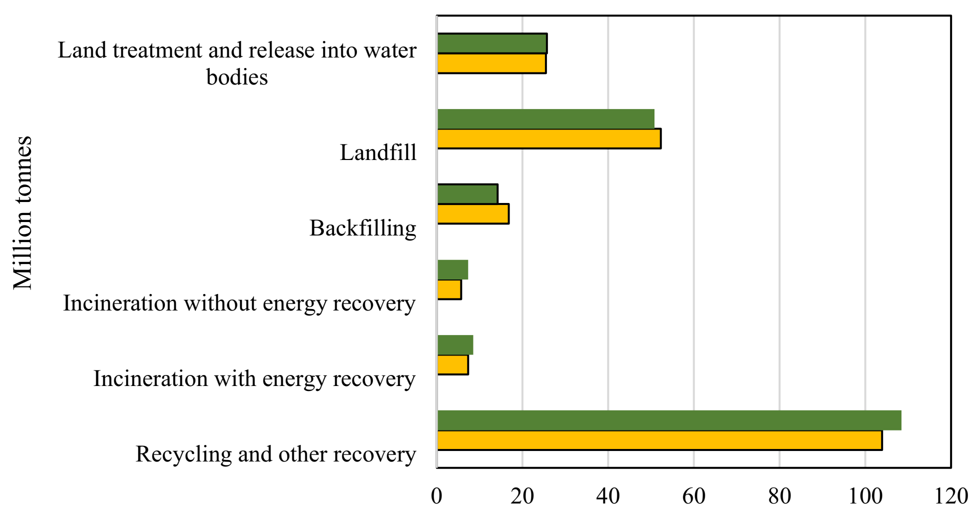
The recycling rate has increased by a negligible 4.3% in this period, whereas the use of incineration facilities without recovery methods has increased significantly, reaching 28.3%. These changes highlight the role landfill taxes played in encouraging incineration. However, it is crucial to recognize that there could be an increase in GHG emissions linked to these incineration facilities, particularly without recovery facilities, resulting in the need for thoughtful deliberation and mitigating measures. Even though the landfill volume treatment rate has dropped to 2.8%, stepping up waste management (WM) procedures in the UK is still crucial. This is essential for raising the recycling rate and lowering landfill utilization rates. An improved WM hierarchy, including the environmental impacts of each metric (discussed in the circular economy part), is crucial to advancing toward more sustainable and effective waste handling and disposal practices.

Through addressing waste management issues and advancing resource recovery, technological improvements in waste treatment systems substantially influence the reduction in UK GHG emissions in the waste sector. One of the efficient ways to reduce GHG in this sector is by capturing methane from the pyrolysis process in the chemical recycling of waste or burning the waste in incineration facilities with energy recovery and a carbon capture system [71]. Moreover, to limit methane leakage from landfill sites (the primary source of methane emissions in the UK) and avoid related environmental pollution, it is essential to improve recycling facilities to convert waste to fuel or recyclate products to reduce waste sent to landfills [71, 117].

Advanced waste to energy technologies (WtE) convert waste into energy through incineration with energy recovery or advanced thermal waste treatment methods such as pyrolysis, gasification, hydrothermal liquefaction, and anaerobic digestion [118]. Advanced WtE generates energy through heat, electricity, or biofuels and keeps waste out of landfills, where organic matter breaks down anaerobically and releases methane, a potent GHG [119, 120]. WtE technology displaces energy generation based on fossil fuels, which lowers emissions overall [121, 122].

Some studies state that WtE reduces GHG emissions in the UK and depends heavily on recycling and energy recovery obtained from waste. They state that 44% emission savings on average can be achieved using technologies including incineration with energy recovery, mechanical heat treatment, and mechanical biological treatment [123, 124].

Another efficient practice in waste treatment methods in the UK is advanced thermal treatment technologies, such



	Recycling and other recovery	Incineration with energy recovery	Incineration without energy recovery	Backfilling	Landfill	Land treatment and release into water bodies
UK 2018	108.4	8.5	7.3	14.2	50.8	25.7
UK 2016	103.9	7.3	5.7	16.8	52.3	25.5

Fig. 7 Treatment methods in the UK (million tons), 2016–2018 [112]

as pyrolysis and gasification, for recovering energy and recycling valuable materials. These methods use high temperatures to transform waste into syngas, char, and fuels, with lower emissions and environmental effects than typical incineration facilities. Thermal treatment technologies contribute to GHG emission reductions and support a CE approach to waste management by diverting waste from landfills [124–127]. Findings indicate that the GHG emission drop from these plants is around 74% compared to landfills [128], which highlights the necessity of developing these waste treatment methods.

Additionally, anaerobic digestion (AD) is a biological process that degrades organic waste without oxygen, yielding biogas (methane and CO_2) and digestate (a nutrient-rich fertilizer), which can be used as one of the waste treatment methods in the UK context [129–131]. Technological developments in AD systems, such as improved reactor designs, pre-treatment technologies, and biogas purification processes, improve process efficiency, boosts biogas yield, and reduces organic waste decomposition emissions [131–134]. AD produces biogas that can generate energy, heat, and fuel vehicles, replacing fossil fuels and cutting GHG emissions. Additionally, it is a cost-effective method of energy generation compared to WtE [130].

According to UK governmental reports, AD has already reduced carbon emissions by over 1% and has the potential to lower them by a further 6% [135]. In the UK, AD plants generate over 19 TWh of biogas annually, with approximately 6.5 TWh converted to grid-ready biomethane, equivalent to 3.8 million barrels of oil [135, 136]. Currently, the UK government encourages the recycling of food waste by AD to produce biogas through a number of tax reductions on the feed-in tariff (FIT) scheme based on the environmental program's goal of promoting renewable usage and low-carbon electricity generation [44]. Finally, technological advancements in waste treatment methods are instrumental in reducing GHG emissions in the UK by diverting waste from landfills, recovering energy and resources from organic waste streams, and promoting a more sustainable approach to waste management. Continued innovation and investment in these technologies are essential for achieving the UK's waste management and climate goals while supporting the transition to a low-carbon circular economy.

Law and policy of waste management in the UK

In the UK and other European countries, efforts to reduce GHG emissions through waste management regulations and policies have shown promising results by prioritizing recycling, composting, landfill taxes, and energy recovery schemes [137, 138]. Investigations show significant progress in increasing recycling rates in Germany and Austria by around 70 and 60%, respectively [139–141]. The EU has made tremendous advancements with the Landfill Directive law in 1999, which aimed at preventing waste from landfills. Methane emissions from landfills have decreased due to investment in composting, recycling infrastructures, anaerobic digestion by applying methane capture for use as green energy, and waste incineration with energy recovery.

Despite a 30% increase in recycling rates, landfilling remains the dominant waste management strategy in the USA (51% of total disposal methods in the USA), contributing to larger GHG releases due to landfill's high organic waste content [142]. According to reports, the waste sector in the USA was responsible for 14.5% of total methane emissions in 2020 due to landfill emission generation [142–144].

Data availability for GHG reductions from waste management in Africa and Asia is limited. Asia and Africa tackle particular issues due to rapid urbanization and industrialization, which results in massive waste generation [145–147]. However, countries like Japan and South Korea have established effective waste management systems through decarbonization of the entire life cycle of each material via material cycles [148, 149] to limit the relevant environmental impacts and GHG reduction, particularly in increasing the recycling rate by over 80 and 60%, respectively [148, 150–152].

In contrast, other Asian countries struggle with waste management systems and GHG reduction due to lower recycling rates, inefficient recycling facilities, open burning and uncontrolled landfills [150, 153]. For instance, India's recycling rate is 20%, which needs more recycling development and an advanced waste management system to drop GHG emissions as one of the leading countries in GHG production [154–156]. In Africa, between 4 and 10% of waste is recycled, and the rest is burned in the open area or disposed of in landfills [157, 158].

These studies demonstrate regional variations in waste management implementation and emphasize the need for coordinated efforts to increase sustainability and lower GHG emissions worldwide by imposing national and international rules and regulations as well as international collaborations and knowledge-sharing facilitating the exchange of best practices and innovative technologies, enabling countries to improve their waste management systems further and achieve greater reductions in GHG emissions [159, 160]. The review primarily focuses on the UK, highlighting improvements and gaps with other nations in reducing greenhouse gas emissions policies from waste management.

Based on the "European Commission" frameworks for waste management systems in 1989, the UK published the "Environmental Protection Act" in 1990 to consider the effects of waste on the environment. Five years later, in 1995, the UK revised and issued the 'Doing Waste Work' strategy for England and Wales with sustainability terms in waste management to decrease the sending of waste to landfill sites and more reusing of wastes. In 2000, England and Wales's "Waste Strategy" publication followed sustainable development by managing waste and using natural resources [161].

After 2000, some considerable changes and revised parts regarding "EU waste laws" were implemented in the UK waste strategies in 2007 entitled "Waste Strategy for England", focused on waste generation conditions and disposal methods. "The Waste (England and Wales) Regulations" were provided in 2011 by the UK based on "(WFD)" policies for handling produced waste and the application of waste hierarchy [162]. In 2013, the circular economy's role in using resources efficiently and sustainable economic growth instead of the linear economy to protect the environment and minimize waste impacts on nature was highlighted after some updates in WFD works in sustainability and waste prevention measurements. Therefore, the "Waste Prevention Programme for England" focuses on reducing waste quantities and moving toward a resource-efficient economy through financial support. This program takes actions consisting of three essential aspects [163].

A new "Waste Management Plan for England" was published in 2013 based on "The Waste (England and Wales) Regulations 2011" policies and principles, and critical features and equivalent waste strategies for Wales, Scotland, and Northern Ireland were issued, too. In this strategy, the government provided six UK waste policies, including waste hierarchy, diversion of waste from landfills, increased recycling, reduced waste from the economy, controlling hazardous waste, and shared responsibility [164]. Although this plan concentrates on waste arisings, statistics, and their current management systems, "The Waste (England and Wales) Regulations 2011" focused on the circular economy approach in waste management and using resources efficiently. The UK government issued the updated "Waste Management Plan for England" in 2021 [23]. This revised plan emphasizes sustainable waste management to meet the net-zero emissions target by 2050, aligned with "Our Waste, Our Resources: A strategy for England" and "25 Year Environment Plan" published in 2018. "Our Waste, Our Resources: A strategy for England" consists of essential principles [165] focusing on minimizing waste effects on the environment via waste reduction and reusing material by considering the lifecycle approach and the circular economy model.

This strategy framework aligns with the "25-Year Environment Plan" commitments issued in 2018. In this plan, by identifying the following goals, the UK government intends to protect the natural environment and secure better health conditions for humans and wildlife. This plan's policies set out to double resource productivity by 2050, reuse materials, and minimize waste to control their environmental impact and pressure [17, 166]. The current UK waste policies from 1990 until 2018, with a specific focus on England and Wales, are summarized in Table 4.

It is crucial to evaluate the effectiveness of the UK's present WM policies [17, 163, 167] in addressing the concepts of CE to assess progress and determine areas that need improvement [72, 168, 169]. The UK's waste management framework incorporates policies and programs that promote CE concepts [165, 170, 171]. These include boosting industry resource efficiency, lowering landfilling, and raising recycling rates [172–176]. Further attempts are required in a few crucial areas to conform completely with CE standards.

One aspect is to develop comprehensive and standardized waste collection and recycling systems nationwide. While progress has been made in increasing recycling rates [177, 178], there are still disparities in recycling infrastructure and practices across different areas in the UK [174, 179–182]. Standardizing collection methods and improving accessibility to recycling facilities can help improve recycling rates and reduce waste sent to landfills.

Promoting circular design for production is another area that demands much more work in the UK [183, 184]. There

Table 4 The UK acts, policies, strategies, and regulations in waste management

Year	UK policy	Goals
1990	Environmental Protection Act	Effects of waste on the environment
1995	Making waste work strategy	Sustainability terms in waste management
2000	Waste strategy	Sustainable development for using natural resources
2007	Waste strategy for England	Waste generation conditions and disposal methods
2011	The waste (England and wales) regulations	Managing produced waste and application of waste hierarchy
2013	Waste prevention program for England	Reducing waste quantities and circular economy
2013	Waste management plan for England	waste hierarchy, diversion of waste from landfills, increased recycling, reduction of waste from the economy, controlling hazardous waste, and shared responsibility
2018	Our waste, our resources: a strategy for England	Considering the lifecycle approach and the circular economy model to minimize waste effects
2018	25-year environment plan	Protect the natural environment and secure human and wildlife conditions

is still room for improvement to push manufacturers and producers to embrace more sustainable design principles, manage the whole life cycle of their products and accept greater responsibility for their environmental impact throughout the product lifecycle by strengthening legislation and offering encouragement to support eco-friendly design [185, 186]. In this regard, conducting a life cycle assessment (LCA) for products and relevant manufacturing processes can be a circular attempt to find how the circularity of the product can be obtained from LCA outputs [187–190].

Moreover, more financing for waste infrastructure and innovation is also necessitated across the country to shift to a CE. To enable the recovery and recycling of valuable resources from waste streams, this involves investing in cutting-edge recycling technology, such as material recovery facilities and chemical recycling facilities [118, 191–193].

It will be essential going forward for the UK to maintain giving CE ideas top priority in its waste management strategies and policies. This could entail establishing more challenging goals for recycling, waste reduction, and resource efficiency and putting supportive laws and incentives in place to promote sustainable behaviors in all realms of the economy. Government, business, and society collaboration will be essential to proceed with the CE concepts and meet the UK's 2050 net-zero emissions goal.

Conclusions and recommendations

This article examines the essential components and obstacles of the UK's waste management systems, including infrastructure, technical improvements, policy and regulation, and waste reduction strategies. After reviewing existing literature, it was noted that there is a need for a thorough environmental assessment and circularity evaluation specifically for waste management in the UK.

As highlighted by the review study, developing and advancing waste management methods plays a crucial role in attaining the UK's net-zero goal in the waste sector. Energy recovery, composting, and recycling must be prioritized to lessen the carbon impact. It is necessary to keep funding recycling infrastructure and technology to minimize waste production and shift to a CE model. Implementing best practices and accelerating the transition to net-zero emissions require national and international cooperation and knowledge sharing. To achieve the UK's climate goals, waste management must be integrated into larger climate agendas to promote environmental sustainability.

The issue is that the hierarchy system cannot cover all relevant metrics such as the rate of waste generation, rate of waste diversion, recycling rate, composting rate, efficiency of energy recovery processes, carbon emission reduction, financial savings, resource conservation indicators, and environmental impact indicators. The circularity of each stage in the hierarchy of WM has not been linked to measurable metrics for environmental impact assessment, which directly affects the decarbonization of the waste sector and has only been discussed in practices and procedures.

Sustainable and cutting-edge solutions will shape future waste management in the UK. For example, smart waste management systems and advanced waste-to-energy technology can improve resource recovery and lessen environmental impact. Additionally, encouraging a circular economy and giving durability and recyclability top priority in product design will result in a waste management system that is more sustainable. The UK has made commendable progress in waste management, focusing on waste reduction, recycling, and landfill diversion. The UK strives to establish a sustainable and circular economy through recycling initiatives, strategies to reduce landfill use, and support for innovation. However, challenges remain, including addressing waste export and achieving higher recycling rates. Continued research, education, and infrastructure investment will pave the way for effective waste management practices, ensuring a cleaner and healthier environment for present and future generations. To conclude, a circularity system should be considered for the waste management system instead of a linear hierarchy that can be linked to a relevant metric at each level.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability No data were used for the review study described in the article.

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