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Strategic approach towards sustainability by promoting circular economy-based municipal solid waste management system- A review

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ABSTRACT

The evolution of population and swift urbanization has augmented the quantum of municipal solid waste (MSW) across the globe. The MSW has numerous problems, such as health issues, climate change, societal imbalance, etc. Decision-makers continuously investigate a practical and viable solution for eradicating the solid waste management issue. The circular economy offers a critical solution for managing solid waste with a more organized and constructive approach. The study proposes the key facets to design a solid waste management system driven by the circular economy. The circular economy framework emphasizes the 4 R's- Reduce, Reuse, Recycle, and Recover. The review instils the importance of a waste collection and sorting station, waste treatment methods, and recovery of valuables from waste. The importance of policies and legislation in solid waste management systems with cases of developed countries are also discussed. The study further elaborates on the various aspects of the circular economy, including economic, social, and environmental paradigms. An insight into achieving sustainability through a circular economy-based MSW management system is presented. CE-based waste management offers eco-friendly business models, environmental justice, and upliftment of social well-being. The paper acknowledges the worldwide business groups that have adopted the circular economy and are trying to achieve sustainability. The opportunities cited by globally renowned organizations to limit waste generation and observe material recycling and reuse in their workspace and products have also been highlighted. The study offers an understanding of the system that brings prosperity and harmony to society.

Abbreviation:

MSW	Municipal Solid Waste
SO_x	Sulphur Oxides
OFMSW	Organic Fraction of Municipal Solid Waste
WtE	Waste to Energy
OECD	Organisation for Economic Co-operation and Development

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WEEE	Waste from Electrical and Electronic Equipment
CE	Circular Economy
kgoe	Kilogram of Oil Equivalents
AD	Anaerobic Digestion
MJ	Mega Joules
PAH	Polycyclic aromatic hydrocarbons
IOT	Internet of Things
GHG	Green House Gases
RDF	Refuse Derived Fuel
UN	United Nation
SRF	Solid Recovered Fuel
NO_x	Nitric Oxides
SDG	Sustainable Development Goal

1. Introduction

The augmentation in the accumulation of solid waste is an uncontrollably complicated challenge, and this issue requires immediate attention. According to the World Bank, around 2.01 billion tonnes of municipal solid waste (MSW) is generated annually globally. At least 33% of the waste is not discarded in an environment-friendly system (Kaza et al., 2018). The mismanagement of natural reserves accompanies this and affects the ecosystem negatively (Nevrlý and Smejkalov, 2021). New opportunities must be looked at to meet the needs of people for material and energy and prevent the exhaustion of natural resources. An effective solid waste management system provides one such opportunity to produce secondary materials and energy without hampering the health of the ecosystem. An effective solid waste management system works to administer waste by providing a new source of secondary material and energy without hindering the harmony of a region. This closed loop of materials reusability leads to a waste management model called circular economy-based solid waste management.

Solid waste management is much more complex in emerging nations than in OECD (Organisation for Economic Co-operation and Development) nations owing to limited recycling practice options, unawareness of technology, cost involvement, and ineffective waste management policies (Budihardjo et al., 2022). Countries around the globe face a diversity of urban waste management challenges, comprising a scarcity of complete waste separation and recycling systems, a dearth of waste separation between dry and wet at the initial point, and a lack of complete and precise knowledge about the generated municipal waste (Kurniawan et al., 2021). The number of landfill sites has increased over the years.

Landfills are a severe threat; sometimes, they take infinite years to degrade to their elemental composition. Moreover, leachate leakage from landfills can pollute the soil and water at the ground level. It also pollutes the environment, which poses hazards to people's health. The time consumed by some everyday objects to disassemble if not adequately recycled are plastic bottles 70–450 years, tin cans 50 years, and clothes 35–40 years (Polythene, 2020). The waste sorting process can be simplified if the composition of MSW is roughly known so that effective waste sorting methods can be used. The global MSW composition consists of food and green (44%), cardboard (17%), paper and plastics (12%), glass (5%), metal (4%), wood (2%), rubber and leather (2%), and others (14%) (Sondh et al., 2022).

Ineffectiveness in separating, collecting, and transporting the unseparated mixed waste to dumping sights affects the environmental balance. Segregation of waste diminishes the amount of waste dumped into landfills. Separating and treating hazardous waste can significantly reduce water and air pollution. Disposing of the waste in separate containers is essential for proper disposal. Effective solid waste management includes several states, namely, (i) collection and sorting of waste, (ii) reuse and recycling of waste, (iii) recovery from the waste, and (iv) final disposal of the waste. Each stage holds its importance in strengthening the efficacy of the solid waste management system. In all the stages of solid waste management, local governing bodies and government policies play a crucial role. The segregation or sorting of the waste is significant in having a homogeneous type of waste and also helps in smoother conducting of the waste treatment process.

Thermochemical conversions, such as gasification, incineration, and pyrolysis, are viable options for producing energy from waste (Möllnitz et al., 2021). The desired pre-treatment of waste and increased concentration of desired elements are vital to achieving the input quality required for each recycling process. The job of pre-treatment of waste is to treat the waste so that an almost flawless condition is created for the subsequent treatment process (Letcher, 2020). Several techniques are under practice for the segregation and sorting of waste. These techniques include manual sorting, air separation, trommel screening, magnetic separation, eddy current separator, etc. (Wright, 2020). Waste recycling and separation are essential to avoid sending unwanted commodities to landfills.

The United Nations (UN) looks at solid waste management as an essential issue, which, if resolved, can answer many other prevailing issues. Most of the sustainable development goals designed by the UN are unequivocally or equivocally related to the issue of waste management (Sharma et al., 2021). The issue of climatic shift can be resolved with the opportunity of effective solid waste management. The projected emissions linked to solid wastes will increase to around 2.4 billion tonnes of CO_2 equivalents/yr by 2050 (Kaza et al., 2018). The CE-driven waste management focuses on environmental justice and hence provides an opportunity to mitigate these issues effectively. The CE-driven waste management system has the potential to provide a structure that stabilizes and strengthens the economy, improves natural resources management, and preserves the human rights of each individual.

The Circular Economy (CE) reduces environmental pressure by using natural resources and producing commodities. One of the most significant advantages of a CE is that it concentrates on the overall growth of a region's environmental, social, and economic growth (Kouloumpi, n.d.). Many countries promote a CE to rejuvenate the economic and environmental health of the region (Schulze, 2016). A CE is a constructive approach because it aims to circulate resources within a region's economy, lessening the strain on the planet's resources and reducing the impact of extraction, emissions, and disposal (Lazarevic and Valve, 2017; Vanhuyse et al., 2021). A surprising opinion about CE exists from an assorted set of stakeholders, including business, political, and environmental groups, according to which, in the future, there will be only a CE (Jaeger-Erben et al., 2021). This type of economy can be viewed as an organized framework for sustainable development to improve the three essential sustainability factors (Lei et al., 2021). Also, a frequent evaluation of CE practices based on economic, social, and environmental aspects helps monitor the progress in sustainable waste management. Evaluating the pillars of CE is critical to the region's overall development. The three pillars should develop in harmony with each other for a strong and effective waste management model.

The present study critically presents the different dimensions of circular economy-based MSW management. The study tracks the concept of the 4Rs- Reduce, Reuse, Recycle, and Recover and implements the same in the proposed solid waste management model. The review offers the effectiveness of the solid waste management system by highlighting the importance of waste collection and sorting, reuse and recycling, and recovery of valuables from waste. The critical focus of previously available research is on the environmental aspect and not on all three pillars of CE: economic, environmental, and social. The present study digs into the harmonical growth of social, environmental, and economic fronts to design an efficient solid waste management model. An outlook of a CE is of value material recovery from waste. The recovery of valuable material from the waste can be in the form of fuel, oil, electricity, or treasured materials such as fertilizer, animal bedding, precious metals, etc. The most prominent businesses and organizations in their respective fields adopting CE is a big motivation for the other compatriots and small businesses. Hence, their vision and motivation for this practice are captured in the review to develop a better understanding of what efficient waste management looks like.

A systematic approach was employed for conducting the literature review. This process was employed to capture the most precise and related studies possible. The process involved searching the research articles with the combination of keywords such as "Circular economy", "circularity", "solid waste management", "MSW management", "three pillars of circular economy", "sustainable waste management", "exergy", etc. The articles obtained from these searches were carefully scrutinized based on abstract and title reading. The articles most aligned with the present study were shortlisted for further comprehensive analysis. In the detailed study, the full text of the research articles was carefully read to finalize the papers. Another approach of scanning the references of the shortlisted papers was made to get a sufficient number of research articles to conduct a proper study. Table 1 represents previous work in solid waste management to achieve sustainability with different approaches.

Section 2 includes the role of waste collection and sorting stations, highlighting the importance of waste collection and later sorting to have homogeneity in the waste. Section 3 discusses the 4 R's of waste management: Reduce, Reuse, Recycle, and Recover. This section helps develop a circular economy through an effective solid waste management model. Section 4 discusses the three pillars of CE: economy, environment, and society, from the perspective of the MSW management system. It also presents the vision of the global influencers that embrace CE.

2. Waste collection and sorting station

As much as reducing the generation of MSW is to be controlled, there is also a need for suitable and efficient waste collection. The waste collection comes under the purview of local governing bodies, and in some countries, it is also done by private agencies. Organizing the waste-picking system and processing it further for recycling or treatment has been an excellent task for governing bodies around the globe (Zolnikov et al., 2021). Waste-picking management is complex and challenging (Nzeadibe and Adama, 2015). There is a need to set up a proper waste transfer station system to meet the accumulating waste crisis. The current waste management and collection system status shows that general MSW management facilities lack the resources to function effectively. On top of that, these resources are also being used inefficiently, for example, labour, vehicles, etc. (Salazar-Adams, 2021).

Different methods can do the collection of waste. Some standard practices employed are door-to-door collection, central waste collection points, and collection of waste in the vehicle by notifying through bells or other signals. The waste collection rates vary for both urban and rural areas. In most high-income countries, the waste collection rate is nearly 100%, whereas for low-income countries, it is roughly 39%. The significantly low waste collection rate is due to the lack of proper infrastructure facilities, education about waste, and management efficiency.

The waste collection rate also hinges on the development situation of the area in the same country. It is found that the waste collection rates are higher for the urban regions than the rural ones since the waste collection is an urban amenity. In some middle-income nations, it is found that urban cities have twice as high as rural places (Kaza et al., 2018). Since the waste collection service and administration are complex tasks for the government, the system's privatization is practised in many countries such as Korea, Thailand, Mongolia, etc. The government has highly subsidized the waste collection system to promote privatization. Due to the involvement of private agencies, the efficiency of waste collection increases, and the quality of service also increases. The private agencies can ease some pressure on the government and local bodies by helping.

The waste transfer station is a small storage facility where MSW is stored for the time being before it is ultimately headed to the recycling or waste-to-energy plants. It works as a central place where MSW is collected and stored by the collecting team. Primary tasks conducted at a waste station include unloading from a garbage truck, inspecting and removing nasty stuff (e.g. car batteries), compressing luggage, and moving it to a large vehicle (Lebank, 2020). The location of the waste picking station also plays a vital role in the economics of the waste management system. As the amount of waste increases and the travel time to waste plants increases, the

Table 1
Important features and coverage of the previous research work in the field of circular economy and solid waste management.

Study Approach	Salient Features	Reference
Waste-to-energy (WtE) backed MSW management	• MSW is a renewable energy source. • Different WtE treatment technique is suitable for different waste. • Organic waste- anaerobic digestion; mixed MSW- incineration; plastics, tire, and wood waste- pyrolysis and gasification; inert waste- landfilling. • WtE can majorly reduce GHG emissions for MSW management.	(Kumar and Samadder, 2017; Munir et al., 2021; Varjani et al., 2022)
Green Economy	• The green economy focuses on economic development, poverty mitigation, and environmental sustainability. • Concepts of industrial ecology, CE, and waste pyramid are highlighted. • Cohesion of waste management policies and regulations can help build a green economy.	(Kundariya et al., 2021; Pitkänen et al., 2016)
Circular Economy integrated waste management system	• It focuses on integrating the concept of CE with solid waste management. • Inefficient waste management is the cause of severe health and environmental issues. • Economic growth can be stimulated by CE strategies of recovering, recycling, repurposing, refurbishing, reuse, etc.	(Joensuu et al., 2020; Sharma et al., 2021)
Circular Economy focusing on the environment.	• The acquaintance about green logistics and CE should be promoted to the citizens. • More focus should be laid on reducing the waste at source and the use of resources. • A closed-loop economy's functioning is better than a linear economy.	(Leising et al., 2018; Li et al., 2022; Liu et al., 2021)
Circular Economy	• Life cycle assessment (LCA) can be a vital tool to assess the ecological health of the products. • Circularity indicators are compared with environmental consequences. • The industrial economy and eco-industrial parks have grown in great potential with the growth in the structure of CE.	(Harris et al., 2021; Lieder and Rashid, 2016)
Circular Economy-based solid waste management system	• Practice of CE in solid waste management systems can help mitigate the problems related to waste generation and accumulation. • MSW is a mixture of wastes and therefore requires proper sorting before being moved ahead to the treatment facility. • Effective strategies and policies are required to provide infrastructure to utilize the true potential of waste with recycling and recovery of valuables. • Sustainability in a CE can be assessed in the economic, social, and environmental facets using modern assessment tools such as exergy analysis.	Present study

conveyance cost rises. Therefore, the location of the waste picking station is considered near recycling and treatment plants to minimize costs (Hannan et al., 2020).

Using technologies like the Internet of Things (IoT) is very influential in making solid waste management systems efficient. Maiurova et al. (2022) digitalized the solid waste management network in Moscow and achieved more work using limited resources. The sorting of waste is carried out based on its type. The waste can be plastic, electronic, metallic, organic, etc. A different sorting method is employed for each type of waste and is made ready for the next unit. The different sorting methods include manual sorting, air-density separator, metallic separation, and electrostatic method, as shown in Fig. 1. All of these techniques are conferred in the succeeding section.

2.1. Manual sorting

The wastes that come from the source are of different shapes and sizes. This sorting method separates large waste, such as rocks, stones, wood, oversized clothes, etc., from the other waste. This method is done by labourers mostly with their bare hands. The only equipment involved in this method is a large table or a conveyor belt. Handpicking is probably the most extensively employed technique for separating municipal solid waste. It is also the sole technique for eliminating PVC plastic, e-waste, etc. The construction and demolition waste usually contains concrete, wood, glass, rocks, etc. (Lawson, 2020). The process is very time-exhausting and labour-

Fig. 1. Roadmap of waste management structure: Journey of waste from collection, segregation, and sorting to suitable waste treatment facility.

intensive, but it can be classified in a way that contributes to separating waste and recovering valuable materials. This method is majorly used in countries with cheap labour as only human resources are required in this sorting type. Manually separating waste involves several actions: unloading the waste, spreading waste (with preventive measures), manually separating visible waste for reuse, collecting and storing waste, and collecting the remaining debris after sorting (MOHUA, n.d.).

2.2. Air density separator

This waste separation technique involves using fans or blowers to perform the task. The fan helps create a flow in the upward direction because of the movement of the air in that direction. The separation of the material is achieved by using the method of density difference. This technique's efficiency depends on the airflow's force and how the material enters the air column. A material's moisture content is also essential, as water can squeeze into some materials, causing them to fall and making the different materials stick together ("Solid Waste Management," 2022). The air separation can be subdivided into wind shifter and zigzag type separator. It effectively separates lightweight materials like plastic bottles, different grades of plastic from metals, and heavy wastes.

2.3. Trommel screening

Trommel screens, commonly known as rotating screens, are mechanical screening machines employed primarily for separating materials in the solid waste treatment industry. The trommel has a web-like structure, commonly known as meshes, of various sizes on the surface and consists of a cylindrical drum that functions in a rotational motion. As the trommel rotates, the mesh in the screen permits the separation of specific sizes of waste that form a heap, e.g., manure. The wastes larger than the permissible size of the mesh are blocked in the rear part of the trommel (Chen et al., 2010).

Trommel requires some human resources to operate smoothly, quickly, and safely. Running the same machine for dry and wet waste is also possible. When the drum is inclined, the object is lifted using the lifting bar and then dropped to move further down the drum. Otherwise, the rolldown of the object will be slow. In addition, the lifting bar shakes the object to separate it. In the MSW industry, trommel screens classify fixed particle sizes. By removing inorganic substances such as ash and water from classified light distillates from solid waste, the trommel improves the quality of other fuel-derived solid waste (Goli et al., 2021). After the scrutiny of the MSW in the sorting plant, usually, three significant sets of material are obtained: (i) Refuse Derived Fuels (RDFs) comprising combustible materials, (ii) large-sized materials including stones, metals, electronic material, etc., and (iii) the inert or the delicate material.

2.4. Metal separation

In the mixed waste brought to the sorting station, there is a large proportion of paper, plastics, metals, e-waste, and food waste. The metallic contents of the waste are separated using the metal separator technique. It is an essential technique in a waste separation facility. First, it helps in separating the high-quality material. Second, the removal of metals is crucial for the efficient working of further processes to be carried out, like crushing, visual sorting, and RDF production. Magnetic and eddy separation are the two techniques readily used for metal separation.

2.4.1. Magnetic separation

This method uses an electromagnet to turn the electromagnet on or off to remove the collected metal. A magnet cannot separate all metals (Ding et al., 2021). The setup comprises a rotating drum with a permanent electromagnet installed to draw the magnetic materials from the belt conveyor. Non-iron metals do not contain ferrous content and do not react to magnetic fields. Materials such as stainless steel, aluminium, and copper have weak or no magnetism. Another shortcoming of this method is that microscopic magnetic items will not be picked up when embedded in non-magnetic material (Fitzgerald, 2013). Also, large magnetic items can be dragged along with unwanted objects such as paper, plastic, and food waste. This is most common in mixed recycling streams because the material is collected and segregated before processing.

2.4.2. Eddy separation

Various materials in the e-waste are non-magnetic. One of the significant elements among them is aluminium. Eddy's current separation process usually separates this non-ferrous waste. Eddy's current separation method uses the electromagnetic induction of conductive materials to separate non-ferrous metals based on different conductivity ("Physical sorting – The Eddy current separation method," n.d.). A combination of non-magnetic materials in the specified elemental dimensions range is available to the eddy current separator belt via a conveyor belt. This method is quicker than material supply and can ideally spread the material in a single layer.

The material is transported to the primary pulley separation zone, where the non-metal is repelled from the non-metal host material. Rejected non-ferrous metals are transported to collection belts or bins via strategically placed splitters. Adjusting rotor speed, feed rate, and belt speed can considerably impact the separation speed of standard plastic, aluminium, and copper elements from dry recyclables (Huang et al., 2021). The metallic materials are attracted by the large magnetic force induced within the separator, whereas the non-metallic materials take a free fall into the non-ferrous areas.

2.5. Electrostatic separation

Electronic wastes, commonly known as e-waste, are discarded or dumped electronic wastes such as televisions, mobile phones, laptops, batteries, and many more. Over recent times, it has been observed that e-waste is on the rise in terms of generation, but still, no practical method of waste disposal is known. This is due to the complexity of the components of e-waste. E-waste comprises many toxic metals such as lead, poly-bromine, cadmium, lithium, mercury, and flame retardants that harm well-being. The adverse health

effect of these toxic metal includes damage to the liver, brain, kidney, heart, etc. The e-waste can be sub-categorized into insulators (non-conductors), conductors, and semiconductors. Electrostatic separation can be used for recycling e-waste to separate these insulators (non-conductors), conductors, and semiconductors.

The electrostatic separation technique effectively recycles the conducting and insulating material in the e-wastes (Tilmatine et al., 2009). The e-waste disposal process usually involves dismantling, disposal, and final processing. Disassembly is the first step in separating dangerous and valuable components. Subsequent processing breaks the material to release it from the compound and separate it. The technique works on the principle of electrostatic charges. The electrostatic charge is applied to attract and repel materials with different charges. When an electrostatic separator utilizes attractive forces to classify particles, conductive particles attract oppositely charged objects, such as metal drums, separating them from the overall mixture (Aksa et al., 2013). The printed circuit boards, commonly known as PCBs, contain a majority of valuable metals, as listed by Waste from Electrical and Electronic Equipment (WEEE). These waste PCBs have a high potential for value product recovery, so electrostatic separation of PCBs is an efficient and effective solution (Hamerski et al., 2019; Jiang et al., 2008). The roll-type corona electrostatic extractor can segregate the particulate mixture of plastics and metals (Maammar et al., 2022). The key features of different waste sorting methods are highlighted in Table 2. It also highlights the applications of these methods in the industry.

2.6. Balers and compactors

A problem that waste management organizations face is the volume of space these wastes acquire. However, with the advancements in technology, there are means now by which this space problem can be resolved to some extent. The balers and the compactors are the devices that the user can employ to limit the space that the waste acquires. Four significant baler components are a press channel, a pressing chamber, a tying device, and the power unit ("The Different Types of Recycling Balers Explained," 2021).

The operator adds the waste to the hopper. When the hopper is loaded with the waste, a baler is used to compress the waste into bundles called a bale. The balers compress the waste materials, which can be recycled into smaller, more manageable bales. The balers find their use in many industries, such as retail outlets, institutions, manufacturing, and recycling plants. Two major waste balers are employed: round balers and square balers (Shang et al., 2021). When creating the bales from the baler, the density of the bales is essential. The bale density is one of the most significant features influencing the efficiency of storage, aggregation, transporta-

Table 2
Salient features of various waste sorting methods- advantages, disadvantages and application.

Sorting method	Advantages	Disadvantages	Applications
Manual Sorting	• Possibility of achieving a distinctive fraction of the highest quality • Higher precision in separating materials • Limits the risk of exposing hazardous substances like plastics and other wastes containing pollutants to humans and the environment • Generates employment opportunities	• Too risky for the health of people working in waste sorting • Time extensive • Requires a large labor force • Inefficient	• Waste treatment plant • Plastic recycling plant • Mineral recovery plants
Air Separation	• Provides a clean aggregate of fine/low-density particles • Provides a clean aggregate of large/heavy-density particles • Less time consuming • Easily removes unwanted products	• Dust emission is high • Less effectiveness in separation for moisture-rich materials • Power consuming	• Produces refuse-derived fuel RDF and solid regenerated fuel SRF • Waste to energy (WtE)
Trommel screening	• Large flexibility of materials • Simple working and operation • Large processing capabilities • Low cost and easy to maintain	• Low efficiency • Binding and clogging of material of the trommel mesh • Portability issues	• Mineral recovery plants and chemical industries • Waste treatment plant • Coal screening • Gold mines
Magnetic Separation	• No filter cloth or other consumables are required • Simple working principle • Portable and powerful in material separation • Wide range of use and effective use in liquids • Environment friendly • Provides high productive output	• Requires regular maintenance • It needs regular washing to remove the accumulated material	• Waste plants • Chemical production plants • Agricultural machinery • Liquid treatment plants
Eddy separation	• Negligible loss of valuable materials • Low maintenance • High metal separation efficiency • High yields of non-ferrous metal recovery	• Inefficient for multilayer packaging • It is not practical for metals that can become warm in eddy current fields	• Waste plants and waste-to-energy • Metal recovery in automobile recycling lines • Aluminum separation in glass recycling • Cement mills and power plants
Electrostatic separation	• Recycles e-waste • Recovers high-value metals • Less power requirement • Equipment has low maintenance and high reliability	• Designed for large industries • High voltage breakdown	• Mineral processing • Plastic recycling • Food separation
Automatic separation	• Eliminates health hazards for staff • Accurate and effective • Latest technologies involved	• Complex method • Still not completely developed • Requires specialist technicians to operate	• Waste plants • Waste management system

tion, and handling (Shah and Darr, 2016). Like the balers, the compactors also reduce the waste volume, which helps limit the space acquired in the landfill sites. One advantage of the compactor is that it reduces odour, fire risks, and vermin.

3. Waste management policies, reuse, recycling, and recovery

A sustainable MSW management system ensures harmony in the country or region. Promoting a circular economy-based MSW management system offers a chance to limit the utilization of natural reserves and to preserve the ecosystem by employing the concept of reduce, reuse, and recycling (Li et al., 2021). This characteristic of CE aligns with the Sustainable Development Goal- "*Ensure Sustainable Consumption and Production Patterns*" (SDG-12) and "*Take urgent action to combat climate change and its impacts*" (SDG-13) as adopted by the United Nations (Serrano-Bedia and Perez-Perez, 2022). The policies and legal framework for designing the waste management system are paramount. Sustainability in the MSW management system can be majorly achieved by adopting CE practices. As recycling decreases waste effluence and restores useable fresh supplies and energy, or so-called "misplaced resources," recycling is crucial to sustainable waste disposal (Saleh and Ansari, 2012).

3.1. Waste management policies

A circular economy-powered solid waste management system is laid on the foundation of a robust waste management policy framework. The decision-makers and the local governing bodies design a robust policy module with strict administration to bring the policies into function. The collaborative efforts of the governing bodies and residents can result in an efficient solid waste management system with a circular economy as its prime mover. There should be a focus on a waste management system framework that emphasizes the importance of the setup of institutions for the management and operation, the capacity to promote awareness in the citizens of the region/country, improved structure and practice of laws, guidelines, and adequate infrastructure facilities (Khatib, 2010).

The developing and under-developed countries can take inspiration from some countries leading in the waste management system and adopt their policy framework. Implementing the principles of CE, to reduce the generation of waste at source and to recover valuables from waste, the government of Germany introduced policies such as "Act of Promoting Closed Substrate Cycle" and "Waste Management and Ensuring Environmentally Compatible Waste Disposal" (Sondh et al., 2022). The countries leading in solid waste management always focus on strengthening public policies. The involvement of the citizens in these policies helps to build a sense of responsibility among them to run the system smoothly and efficiently. The developed countries in Latin America primarily focus on establishing a waste management scenario powered by the involvement of the public sector. The policies aim at the elimination of waste through the treatment process. The public agencies design a system that is cohesive, efficient, and sustainable (Gouveia, 2012).

A CE-driven waste management system requires the government to function with a business model, implementing services and augmenting the utilization of natural resources with a motivation to improve the economic and monetary profitability of the country. Simultaneously, the government should focus on safeguarding the environment and improving social well-being. Most of the European countries have turned their attention towards the energy scarcity state. Due to these circumstances, these countries have focussed on waste as an alternate resource to energy. An approach from such countries has seen a reduction of solid waste being moved to thermo-chemical treatment plants, which can produce energy as a major product. In Portugal (Batista et al., 2021), Decree Law No. 178/2006 highlights the importance of recovery from waste rather than disposal.

Since the early 1990s and 2000s, Germany has focussed on energy as a crucial element for their nation's prosperity. A term was introduced, "Energiewende", which is defined as "growth and prosperity without petroleum and uranium". This approach has been a part of the German policies to nurture their state. The utilization of renewable sources for energy production has been a significant concentration of the policies. The cities in the country were developed to have resource-wise provinces to encourage wiser usage of the resources in Finland. This policy focussed on easing the environment burden and reducing further aggravating the situation of the environment. This resource understanding was employed in the city strategies of the country (Jyvaskyla, 2015). Another policy from Finland was introduced to put effort into reducing environmental emissions. In 2008, HINKU- a carbon-neutral municipality-focused on reducing greenhouse gas release into the environment. The organization aims to reduce the overall emissions in 2030 by 80% as in 2007. This strategy aims to develop social and environment well-being by reducing greenhouse gas emission levels (Pitkänen et al., 2016).

Technical advancement is imperative for a robust solid waste management system. Developing new technologies and improving existing ones helps overcome technical barriers. It also helps in making more efficient and more sustainable solutions that are cost-effective to employ practically. The policies also follow a similar path, where new and better policies are to be framed to practice them and attain the target of sustainable development. However, the policies cannot be practised until the technological advancement in the processes is completed.

3.2. Waste reuse and recycling

The waste sorting and segregation process comes in very handy for classifying the wastes as per their final treatment. The sorted waste can be further referred to as a recycling plant, treatment facility, or landfill, depending upon the reusability potential of the waste. A preference is given to waste reuse and recycling of material due to the conscious efforts globally to preserve conventional resources and environmental safety (Cudjoe et al., 2021). Recycling these waste materials, such as metals, plastics, papers, etc., helps limit the use of virgin resources for commodity production (Tang et al., 2020). Recycling offers better environmental health due to the ease of pressure on natural resources to produce new commodities from virgin materials. The concept of "zero-waste" can be achieved by maximizing the recycling rate (Nevrlý and Smejkalov, 2021). Research and innovation in waste recycling and reuse are taking

place rigorously to bring circularity to the economy. The practice of recycling a variety of solid waste constituents for use in making concrete blocks, including waste glass, crushed brick, recovered concrete, tile waste, ceramic, etc (Luhar et al., 2019).

The practice of recycling in a country or a region also depends upon the nation's income level (Moroke et al., 2019). The network for MSW collections is well-knitted and works effectively in high-income countries. The efficacy of the material collection also significantly increases the recycling and reusability of materials. As for middle-income and lower-income countries, the waste collection system isn't compelling enough to endorse the reuse and recycling of waste ingredients. In such countries, open spillage and waste dumping are practised for disposal (Munir et al., 2021). For high-income level countries, the recycling rate is much higher than those with low-income levels. This is due to the practice of much more competent waste management systems and recycling plants in high-income countries than in low-income countries (Ferronato et al., 2019).

Middle and lower-income countries have poor solid waste management systems for many other reasons, such as poor education campaigns, lack of public awareness of recycling; inefficient engineering capability, and poor collection systems (Ayeleru et al., 2021). The top 5 countries leading by the recycling rates around the globe include Germany (56.1%), Austria (53.8%), South Korea (53.7%), Wales (52.7%), and Switzerland (49.7%), respectively. These countries follow the policy of limited waste disposal to the landfills, banning particular types of waste, involvement of private companies in waste collection, imposing penalties for non-recycled waste types, etc. (Alex Gray, 2017). Such policies and steps by the governing bodies are beneficial for limiting the spiking of waste at the landfills and bringing circularity to the economy.

An effective MSW management system involves several stages, from the waste collection and sorting system, recycling and reuse plants, treatment plants, and post-treatment disposal (Cohen et al., 2021). All the stages are essential, as lagging in any of them makes the system inefficient. In developing countries, there is high pressure to exploit and over-burden the environment with extensive use of natural resources. This is majorly due to the significant focus on providing a better living standard to the countries' residents and meeting other waste management demands. To accomplish such issues, the governing bodies and policy framers in government play an important role. The type of techniques to be brought into practice, the type of waste management model, and the framing of the policies for effective waste management are some of the decisions to be made by the governing bodies (Bui et al., 2022).

There is a need to include recycling units in the waste management systems to accomplish waste management goals. The concepts of CE and recycling go hand in hand to attain sustainability in solid waste management. An alliance between the public and private sectors is essential for obtaining the desired impact on the system (Silva de Souza Lima Cano et al., 2022).

3.3. Waste treatment facility and waste recovery

For the smooth functioning of a CE, waste volume minimization and the disposal of waste are essential. Not long ago, after waste collection, landfilling was the end destination for waste disposal. Due to this reason, in many big cities, there are big mountains of solid waste (in dumping sites), which in turn becomes a breeding ground for many diseases and environmental issues (Liu and Liu, 2021).

With people becoming more conscious about the environment and climatic issues, many techniques for proper waste disposal are introduced. The waste disposal techniques can be classified as biochemical methods (anaerobic digestion, composting, etc.) and thermo-chemical methods (incineration, gasification, pyrolysis, etc.) (Li et al., 2016), as shown in Fig. 2. About 40–70% of the worldwide generated MSW comprises decomposing organic matter called the Organic Fraction of MSW (OFMSW), the main component of which is food waste (Ali et al., 2017). The biochemical methods are usually time-consuming, taking around 25–40 days, to treat the waste. It also limits the type of feed it can treat (usually organic waste). However, the flexibility to intermittently add raw materials to the digester makes it a simple waste volume reduction and management method.

The other type of waste treatment technique is the thermo-chemical process. Thermo-chemical processes require a substantial quantity of heat energy to initiate the process. The operating range of temperature for these processes varies from 350 to 1500 °C. The processes are comparatively fast concerning biochemical processes. The residence time varies from 4 h to 0.5 s (Nanda and Berruti, 2021). Due to the high processing temperature, treatment for nearly all types of waste is possible. Reducing waste volume is an essential criterion for a waste disposal plant. Thermo-chemical processes reduce waste by 75–90% (Munir et al., 2021). One of the biggest challenges faced by thermochemical processes is that most of the processes are not environment friendly as many pollutants, such as furans, NO_x, SO_x, PAHs, dioxins, etc., are released during the processes. In incineration, a significant fraction of NOx and SOx emissions occur due to excess oxygen (Kumar and Samadder, 2017). Even gasification emission of particulate matter (PM), tar, alkali compounds, HCL, etc., is frequently observed (Upadhyay et al., 2019a, 2019b, 2020).

Research is carried out to limit these emissions by changing the process parameters and operating conditions. Upadhyay et al. (2019c) studied the effect of changing the equivalence ratio to reduce the emission of tar and PMs. The pyrolysis process offers an immediate solution for the NOx, SOx, PAHs, and dioxins emissions due to the necessary condition of an oxygen-starved environment, as no oxidation will occur (Sipra et al., 2018). However, in pyrolysis, there are also pollutants such as heavy metals, nitrogen, etc. (Hasan et al., 2021). The authors' previous work explains a detailed study of the various waste treatment techniques, such as incineration, gasification, pyrolysis, anaerobic digestion, composting, etc. (Sondh et al., 2022).

Recovery of valuables from waste is vital in the CE as it eases the pressure on nature for resource exploitation. Due to the material recovery, the use of virgin material for production will slow down and thereby help build a balance in the environment. A CE provides a valuable solution for upgrading a single-dimensional economy (take-build-use-dump) to a multi-dimensional closed-loop economy (take-build-use-recycle-recover-reuse). The CE introduces a balance in an ecosystem with harmony in economic and ecological development (Geng and Doberstein, 2008).

The wastes from the sorting plants are not the end waste, as shown in Fig. 3. The RDFs and SRFs (Solid Recovered Fuels) separated from the trommels are potential fuels (Tomić and Schneider, 2020). They are of great use to the world in different forms. The dry

Fig. 2. Comparative diagram of the technical features of various waste treatment methods: anaerobic digestion, incineration, gasification, pyrolysis, landfills, and composting.

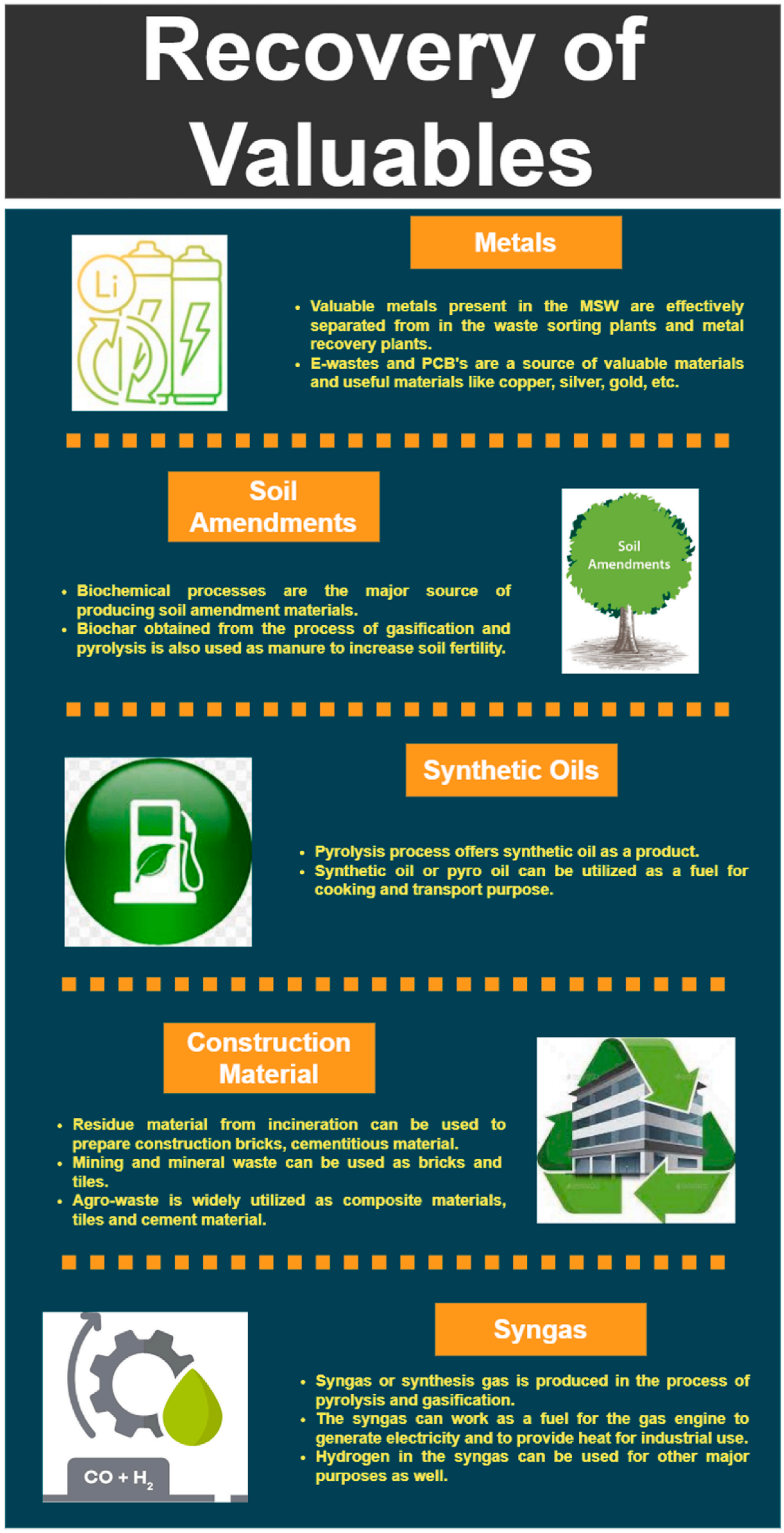

Fig. 3. Valuables attained from various waste treatment processes in the form of metals, fertilizers, oils, construction material, and synthesis gas – waste to resource.

shredded waste containing organic matter can be used as fuel or energy (Mandpe et al., 2022). The induction of Waste-to-energy (WtE) technology offers a great pathway to generate energy from MSW and decrease greenhouse gas (GHG) emissions from incineration/landfill (Korai et al., 2016). Many WtE plants are working on different thermo-chemical processes that can use this waste as an input fuel to generate electricity or energy. Also, the transportation fuels used for cooking, heating, and power generation are produced by the anaerobic digestion of bio-degradable materials or the decomposition of plastic and rubber materials via pyrolysis technology (Chaudhary et al., 2023; Trada et al., 2022).

The rising population has forced responsible bodies to increase energy generation; hence, the misuse of natural reserves and the environment is widespread. This has forced the researchers to devise an alternative energy generation solution. The concept of using solid waste as a potential fuel has come due to research. The waste-to-energy plants offer a quick solution for dealing with the vast waste volume and generating energy in return (Varjani et al., 2022). WtE plants have grown globally over the years due to their fast processing time and valuable end products (Moya et al., 2017). Both the biochemical and thermo-chemical processes can produce energy as a product during the waste treatment process. In anaerobic digestion and biogas plants, methane gas is released predominantly, which can be used as a fuel gas for cooking food. The anaerobic digestion plants generate a net energy production of 9–13.5 kgoe/tonne of MSW. In net energy generation, the thermo-chemical process dominates the biochemical processes. A net energy generation of 36–45, 36–63, and 45–50 kgoe/tonne of MSW occurs in incineration, gasification, and pyrolysis, respectively (Munir et al., 2021; Sondh et al., 2022).

Apart from the electrical energy, an enormous amount of heat energy is also produced, which can be used as a secondary heating source in many plants, devices, oil, and other liquids. Sun et al. (2015) utilized the heat from the horizontal fixed bed to sustain the self-pyrolysis of oil.

The residuary material from incineration can be used as road construction material, construction bricks, and cement material preparation (Zhang et al., 2020). The biochar from the biomass plant can be used as soil amendment material and as an activated char in water purifier technologies. Due to the metal content in the outstanding amounts in MSW, the incineration fly ash also has a metallic content that can be recovered (Bakalár et al., 2021). The compacted waste is sent to landfills, occupying less space than untreated waste.

The inert extracted from the trommel is used in landfills to reduce the reactivity of the waste to the atmosphere in the landfills. More than 95% of indigenous wastes are utilized to generate energy or produce valuable materials. The rise of the electronic industry over the past few years has been intimidating. Electronic equipment like cell phones, laptops, and television is prevalent. With this thought, e-waste generation is also very high.

There are few technologies to effectively dispose of e-waste, commonly found dumped in landfills (EPA, 2021). Even after dumping, these e-waste are valuable due to their potential for material recovery. Useful materials such as indium, aluminium, gold, ferrous material, etc., are readily recovered from the e-waste. The LCD panels of televisions and computers are recycled and urban mined to recover indium, which can be again used for the screens of new electronic equipment, thus bringing circularity to the economy (Akcil et al., 2019).

The pyrolysis process can be classified into three types: slow, fast, and flash, depending on the heating rate. Based on this classification, the product of pyrolysis also differs; it provides pyro-oil (Bridgwater, 2019), bio-char (Tripathi et al., 2016), and syngas (Chen et al., 2014). Torrefied biocoal can replace conventional fuel in thermal power plants or kilns.

The biochemical processes offer a great resource in the form of digestate, which can amort soil quality by providing the necessary minerals (Ascher et al., 2019). The digestate can also be used as bedding for animals (solids), bioplastics, etc. (EPA, 2022). The valuable materials from the waste are also recovered during the waste sorting phase; many valuable metals, like gold, silver, copper, etc., are separated from the waste (Tanısalı et al., 2020). A category of composting known as vermicomposting is globally used as a cost-efficient and eco-friendly techniques. It offers worm meal, vermicast tea, and worm casting. It is also used as a disease controller for plants and as fertilizer for the crop (Simsek-Ersahin, 2011).

The researchers practice the recovery of valuable metals from the wastewater from industries and other outlets, biofuel production from the waste, and abstraction of chemicals from living remains. The leachate formed at the landfills can also be utilized for the circularity in the waste management system (Fazzino et al., 2023). The mature landfill leachates, aged 10 yrs, are rich in valuable substances such as ammonium, metals, and harmful pollutants. Treatment of the mature leachates results in removing harmful pollutants to satisfy its safe discharge. The leachates are useful in AD due to better buffering capacity, lesser suspended solid content, and a nitrogen source to balance the carbon-to-nitrogen ratio. The digestate obtained from the mature leachate-powered AD process improves the soil amendment properties owing to the existence of humic substances and nitrogen concentration (Lv et al., 2021).

4. Sustainability in circular economy-based MSW management system

MSW management systems must adopt CE policies and models to support a larger vision of sustainability in the nation (Mhatre et al., 2021). Sustainability is "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987). The basic framework of the CE addresses three central pillars: economic development (Techno-Economic Aspects), social upliftment (Social aspects), and a healthy environment (Environmental aspects). Sustainability in the MSW management system is said to be achieved if there is a healthy reception for all three pillars (Gadaleta et al., 2022). This acceptance is achieved once the policy decision-makers make conscious efforts to develop an efficient and reliable system framework. A practical framework designed to obtain a healthy economy, society, and environment can offer sustainability in a region or a nation. These three aspects offer different attributes to the CE; a few are shown in Fig. 4.

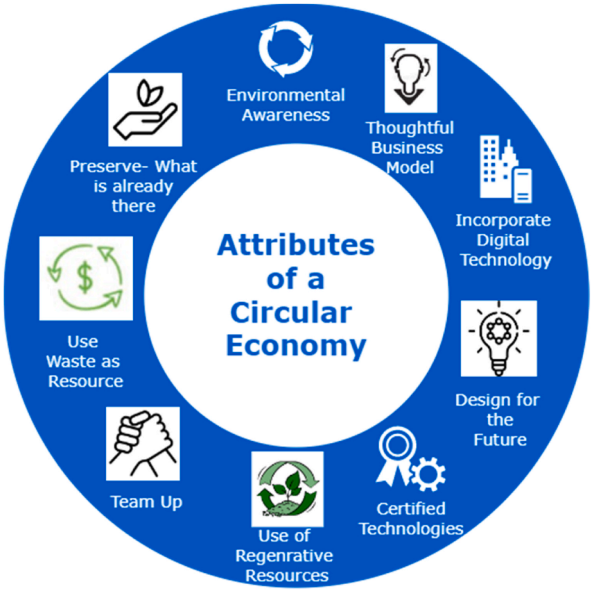

Fig. 4. Principal characteristics of a circular economy to support a solid waste management system involving economic, environmental, and social facades.

4.1. Techno-economic aspects

The effective exchange of ideas and details of materials, their reusability, and recycling highlight a business's critical aspects of sustainability (Leising et al., 2018). The Material Flow Cost Accounting (MFCA) approach is endorsed to improve the efficiency of the material by utilizing the resources; this reduces the cost of producing the commodity and reduces the pressure of resource exploitation on the environment (Nishitani et al., 2022). Economic development can be sustained if the prosperity of the social order in the coming years is at least on the same level as at present (Lassi, 2020). The ideas of resource limitation and recycling of waste are a part of the business model.

The WtE plants influence the economic dynamics to a great extent. As mentioned earlier, only non-recyclable waste is received at the WtE plants to achieve maximum output from the CE model. Among all the WtE plants, incineration has the most commercial reach globally for MSW treatment. Following the World Bank Group (Kaza et al., 2018), around 11% of MSW is treated using thermal incineration. The characteristics of WtE incineration plants are the significant initial investment, low cost of operation, and steady and significant profits. In addition to government waste disposal subsidies and electricity sales, taxes are sources of income incentives, heat supply, and slag sales (Xin-gang et al., 2016).

The plant cost depends on several parameters, including the plant's size, waste type, life cycle, and plant availability (Santosdos et al., 2019). The cost of developing a WtE facility varies from country to country as per their technology readiness and resource availability. Wu (2018) highlighted the difference between developing WtE facilities in China and the US. China developed the facility for a standard cost of USD 250 per annual ton with a comparatively small lifespan. However, the cost of the WtE facility in Europe and the US was figured to be USD 840 per annual ton with a lifespan of 30 yrs. The cost of WtE facilities for some other countries is Ethiopia (USD 343 per annual ton), Vietnam (USD 353 per annual ton), and Sri Lanka (USD 1136/MWh) (Daily, 2017; Wu, 2018). The return on investment (RoI) estimates the total profit or loss made on investment after accounting for the cost. Overall, the RoI on the WtE plants is encouraging at around 18–25%. The income from WtE plant electricity generation in China was approximately 70–85%.

For biochemical plants, anaerobic digestion, composting fermentation, etc., are a few of the primary methods used. Only the biodegradable type of waste can be used for treatment. The biogas plant cost also depends on the same parameters as that of WtE plants. An anaerobic digestion plant in Brazil costs around USD 130/MWh for a capacity of 300 tons/d (Santosdos et al., 2019). An anaerobic digestion plant in Australia costs around USD 7.2 million for a capacity of 35,000–50,000 tons/yr (Usmani et al., 1996). A similar plant in Bolivia costs around USD 6100/kW of electric generation (Perez Garcia, 2014). The cost of a biogas plant in some other countries is Namibia (USD 860), Nigeria (USD 874), and South Africa (USD 3487) (Amigun and Von Blottnitz, 2010). Besides the installation costs, externalities must be considered to evaluate these technologies' synergy successfully. In Greece, the expense of externalities for landfills is around USD 1.71 per ton of MSW, owing to the negative influence on water, soil, and air (Samarasinghe and Wijayatunga, 2022). The RoI for the biogas plants from the literature was around 54.22%, with a payback period of 18 months (Bai et al., 2022).

The economic aspect of the CE is also motivated towards working in eco-friendly business models and activities. It focuses on controlling resource exploitation by managing the already available assets in the market and developing new innovative materials from scrap. Business ethics are essential to implicate economic circularity, based on "What is right to do?" and "What should be avoided for a larger success?".

4.2. Social aspect

The impression of CE is based on the harmonical balance of a region's environmental and economic health. The citizens in the region and their environmental consciousness level define their socio-ecological health status. The municipalities or other similar governing bodies are the central body that introduces various policies to promote a CE in a region. These policies generate employment, wealth, a healthy economy, and a flourishing society (*The role of* municipal policy in the circular economy, 2019). Most economies are built, and focusing on the environmental and social facets is left out for a long time.

The role of the people in the CE and the growth of people in the same are to be evaluated for the betterment. Entitling residents to infuse inside the subject of public movement is one of today's critical, demanding situations in coping with society and environment-related subjects (Antoine et al., 2020). As per the Rio Declaration on Environment and Development ("Rio Declaration on Environment and Development," 2006), policies for the public on environmental troubles can be practical and applicable after they entail the participation of all eligible citizens. There should be a well-built civic engagement between the governing bodies and the citizens to make them feel responsible and connected with the policies for improving environmental health.

A responsible citizen is significant for the growth of any locality, state/province, or nation. Active participation of citizens in public policies at different levels can invoke a sense of responsibility and a feeling of acceptance. The citizens can take the initiative in the personal and public domain to solve socio-economic issues. The education level of the citizens and the educational institutions can also help build a robust CE. As quoted by Roudil (2017), Director of the United Nations Educational, Scientific and Cultural Organization United Nations Educational, Scientific and Cultural Organization (UNESCO): "*Universities and higher education networks can conduct research and provide advice and guidance on strengthening national education systems as well as aspects of capacity building for sustainable development across different sectors; high education subjects can strengthen the interface between research findings and decision-making using evidence-based data, as well as problem-based scientific research*". The educational networks can predict the challenges faced in implementing a CE and impart an effective solution.

Collaborations with universities and educational institutes for research-based activities to develop a framework model of CE are an excellent option for a strong and steady economy (Serrano-Bedia and Perez-Perez, 2022). The availability of employment can be viewed as an essential means of social sustainability as it influences an individual's societal wellness and socioeconomic status (International Labor Organization, 2013). CE can be presented as a new business model focused on new employment opportunities (Burger et al., 2019). Ellen MacArthur Foundation defined CE as " [A CE is] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" ("Circular Economy - Introduction," 2012; Memon et al., 2021).

The generation of employment to the citizens due to the practice of CE generates harmony in the citizens and acceptability towards the model. Employment opportunities primarily improve the lifestyle and well-being of the people. The social aspect of the CE ensures the human rights of the citizens to breathe fresh air, a safe working environment, and cultural integrity. The workers in the waste management plants must be ensured of safety kits like masks, gloves, and glasses. These safety kits are necessary to protect them from lungs and other diseases due to high medical risk. Ensuring a region's cultural integrity helps increase the satisfaction level and happiness index of the citizens of a region.

4.3. Environmental aspect

The environment is also an influential criterion for defining CE importance. The health of the environment, the burden of urbanization, and natural resource management are the key parameters that a CE focuses on. The different parts of society, like industries, institutions, residents, and restaurants, affect the environment. The waste and emissions generated from them deteriorate the health of the environment. In the European Environment Agency (EUA) view, the CE is the substance for the green environment, which is focused on improving humans and society, a resilient environment, etc. (Li et al., 2022). Preserving biodiversity is a top priority, as the significant focus of fundamental CE operating principles is to sustain a rich ecosystem. Habitats must not be adversely affected or physically affected by human interventions. Conservation of biodiversity is one of the critical provenances of biosphere resilience. Physical and energy losses are accepted to maintain biodiversity. Toxic and harmful material should be minimized, held on to in a tightly controlled cycle, and eventually removed. In a CE, economic activity threatens the fitness of humans and well-being. For example, effectively recycling e-waste by burning it above an open flame leads to recycling but is not considered a "circular cycle" (Gladek, 2017).

The WtE plants are modern technologies that move the solid waste management industry towards zero waste and harmful carbon emissions (Kearns, 2019). The emissions (Munir et al., 2019, 2021) from different waste management processes are provided in Table 3. Efforts are also made globally towards reducing the emission of other harmful pollutants that deteriorate the environment's health. The efficiency with which the natural resources are used helps generate economic circularity. Efficient use of natural resources ensures more durability, easing environmental pressure. CE can offer to regenerate the environment by balancing resource management (Velenturf and Purnell, 2021). The circularity in the solid waste management economy is sincerely related to the environment's health. The eco-friendly business models can ensure it as they will ensure more productivity by exerting less pressure on the environment and using readily available assets.

4.4. Exergy-based analysis

The economic loss from a process can be deeply analyzed by applying the concept of exergy. The exergy-based analysis is a powerful tool to strategize, enhance, and assess thermodynamic systems. One of the advanced tools used nowadays to study the techno-

Table 3
Summary of pollutant emissions for various biological and thermochemical waste treatment processes.

Pollutant	Anaerobic Digestion	Composting	Incineration	Gasification	Pyrolysis
CO_2 emission (Tonne per tonne of MSW)	1.19	1.61	1.67	1.3–1.5	0.7–1.2
NO_x (μg/m^3)	–	–	Below 400	Below 200	Below 40
SO_x (μg/m^3)	–	–	40	19	35
Particulate Matter (μg/m^3)	–	–	20	14.1	5.7
HCL (μg/m^3)	–	–	–	3–26	10–50
Hg (μg/m^3)	–	–	–	<0.007	–
Dioxins and Furans (μg/m^3)	–	–	<0.0903	–	–

economic aspect is exergo-economic analysis. Exergy is defined as "maximum useful work obtained from the thermodynamic system when it is brought to thermodynamic equilibrium through a reversible process". A direct association of the exergy destruction can be established with the economic losses and depletion of the resources (Aghbashlo et al., 2022). The exergy destruction signifies the wastefulness in the system. It is the factor to be minimized to maximize the practical work obtained from the system. The exergy analysis finds its application in developing an understanding of the sustainability, output facet, and efficiencies.

The exergo-economic analysis helps identify, quantify, and interpret the economic losses for the systems working. The critical feature of exergo-economic analysis that outperforms techno-economic analysis is its ability to interpret for thermodynamic losses. The accountability of thermodynamic losses helps to study the processing unit on a component basis and, therefore, helps find the deep cause of losses rather than a superficial study. The exergy rates for the different streams involved in the thermodynamic process are evaluated. After that, the exergy indicators are assessed for the significant components and the processing plant. The exergo-environmental analysis is associated with the study of resource exhaustion and the ecological burden of the processing system.

The exergo-environmental analysis identifies and analyses the location, size, source, and environmental influence of thermodynamical incompetence in the energy processing system. Exergy destruction can be found in agreement with greenhouse gas emissions. The study based on the productivity perspective of the process helps establish an understanding of the burden on the environment. The exergo-environmental method successfully manages the shortcomings of the life cycle assessment (LCA) analysis in estimating the sustainability of the processing system by dealing with the environmental load of the transitional products (Soltanian et al., 2022). The interaction between the different components can be utilized to amend the overall performance of the processing system. The quality of the processing system investigation can be enhanced by reducing the exergy destruction in each system component. Each component's environmental impact and investment cost should be categorized into avoidable and unavoidable (Tsatsaronis and Morosuk, 2016).

The exclusive blending of exergy, environment, and economy can effectively evaluate the economic feasibility, thermodynamic yield, environmental well-being, and sustainability of energy and solid waste conversion processing systems. The worthiness of conclusions obtained from exergy-based approaches for advanced study can reveal the interactions between the processing systems' energy and output products. It also measures the preventable part of the thermodynamical inefficiencies, economic deficits, and environmental problems.

4.5. Global influencers embracing circular economy

A CE can be a success if it is practised at different levels of society. The extensive industries and brands people look up to can help by being a role model to those transitioning from a linear economy to a CE. The various aspects of CE and their role are shown in Fig. 5. One industry that has promoted CE globally in recent times is the electrical industry. In the early days, due to the limitation of the poor second-hand market, the electrical industry was one of the most significant contributors to waste. The electrical equipment is built with a simpler technology that is easy to repair. Also, raw materials such as cables, wires, and electrical devices can be reused for other purposes. With innovative thinking and the application of effective circular business models, the contrast in the electrical field has changed (Davey, 2022).

In the architecture industry, "DOOR Architecten", with a brand presence in the Netherlands and Belgium, has adopted the CE and uses discarded scraps to design offices for their clients (DOOR, n.d.). The founders of DOOR Architecten believe that "*With strong, refreshing designs and strategies, we strive for a future-proof living environment that runs on a CE. Amsterdam's circular policies actively* support *us in achieving our ambitions. We* support *these policies by spreading our circular impact in our field of work*".

Global sports brand NIKE also embraces the CE. It claims that around 71 % of sporting brand footwear comprises recycled materials from manufacturing plants ("Nike Embraces Circular Economy," n.d.). The brand also openly endorses sustainability and plans to achieve zero waste in its production process, promote renewable energy-based technology in factories, and minimize emissions during product manufacturing. According to the President and CEO of Nike, Mr. Mark Peter, "By creating low-impact and regenerative materials, we can continue to move toward a high-performance, closed-loop model that uses reclaimed materials from the start. Coupled with smarter designs, we can create products that maximize performance, lighten our environmental impact, and can be disassembled and easily reused".

Another sporting brand, Adidas, claims to attain climate neutrality in its production process (Adidas, n.d.). By 2024, 100 % recycled polyester will be used to manufacture its products. They work under the "made to be remade" tag, which promotes circularity in the production chain. In 2019, Adidas estimated to prepare 11 million footwear using recycled ocean plastics. This limits the accumulation of plastics on Earth and avoids consuming other natural resources (MORGAN, 2019). Electronics equipment brand Apple (Apple, n.d.) claims to attain net-zero carbon impact by 2030. They are trying to achieve this by using recycled material, consuming

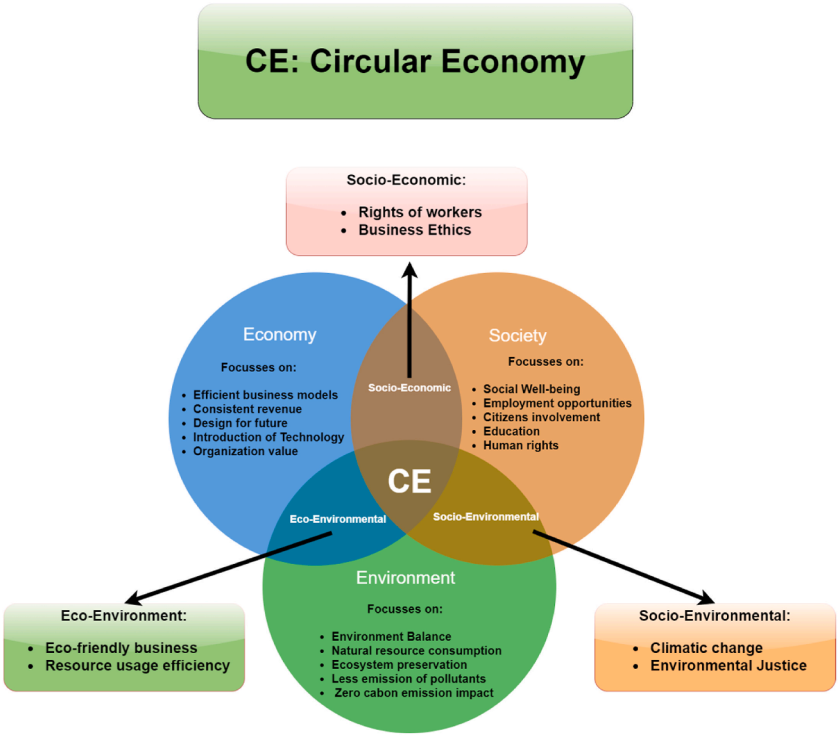

Fig. 5. The key inputs from the three pillars of circular economy: social, environmental, and economic aspects.

less energy, and making the process much more efficient. The company's corporate office works on renewable electricity, again easing the environmental pressure. They also plan to innovate with the materials used in manufacturing and delivering the products, which will directly reduce GHG emissions.

Bread is an essential part of the meal in the US and Europe. The production of bread has increased over time with increased demand. At times, there is a surplus of bread in the market, which ultimately goes to waste and dumped in landfills. Toast is a company majorly active in London, New York, Cape Town, etc., making valuable use of this excess bread to make beer. London Waste and Recycling Board support toast. Toast works on a mission to limit food waste and ultimately help the environment by minimizing the Greenhouse gases (GHG) emitted from food waste (Toast, 2019).

There are other numerous commercial brands and companies which have adopted the CE, like food chain giant "Burger King", furniture brand "Ikea", fashion brand "H&M", etc (Mary Mazzoni, 2020). They all collectively work with a single goal of a CE where maximum utilization of pre-existing resources in the market and adding value to the waste is practised. Drawing from these big brands, even small-scale industries and institutions can develop solutions and models for making the CE in all three economic, environmental, and social pillars.

4.6. Practical implications of the present study

The current solid waste management system is ineffective in dealing with issues prevailing in waste handling. The attempt to redesign the system has been in progress for over a decade. The scientists and concerned authorities provide different solutions. The CE-driven solid waste management system has great potential to overcome the challenges of climate change, energy demand, more extended material utilization, social well-being, etc. When backed with strong strategies and effective policies, the system can work as a catalyst to smoothen the operations. The effort to upgrade a linear economy to a closed-loop economy raises the potential to grow the economy with stability as a critical feature. Also, the utilization of used materials in the system can help in easing out the environmental burden. A CE-driven solid waste management can practice a zero-waste generation policy, leading to sustainability in the waste management system.

5. Conclusions and recommendations

5.1. Conclusions

With the mounting risk of waste accumulation and health hazards, an efficient and cohesive waste management system must be designed to mitigate the issue. The circular economy-driven MSW management system offers a constructive resolution to the existing inefficient system and polishes waste handling. An efficient waste-collecting unit leads to better recycling rates in a region. Sorting of MSW is essential to make it homogeneous and to separate valuables from untreatable waste. The vision of moving towards a zero-waste system is possible with more focus on recycling and recovery from waste. According to its nature, the recoverable waste can be

sent to the recycling and waste treatment facility, while the untreatable can be sent to the landfill. CE-driven MSW management model can not only handle the hazards of waste accumulation but can also ease some pressure on the environment, society, and economy, moving closer to sustainability through better resource management.

Promoting a circular economy-based MSW management system benefits every nation by ensuring harmony on all three fronts – economy, society, and environment. The economic aspect evaluates the feasibility of business models, technology innovation, revenue consistency, etc. Societal subjects such as social well-being, human rights, employment opportunities, citizen engagement, etc, and environmental subjects such as ecological balance, environmental health, emission control, and natural resource preservation are the assessment parameters. These three parameters must be evaluated frequently. Advanced evaluation tools associating these parameters with exergy help better evaluate the quality of the overall processing system. With equal development on all fronts, the CE-driven waste management system can meet the target of achieving sustainability goals.

5.2. Recommendations

The following recommendations are proposed to achieve the full potential of a circular economy-based MSW management system. A strong and efficient waste management system should be focussed on developing a robust policy framework powered by appropriate infrastructure facilities and public engagement. Encouraging private firms in waste collection leads to a more efficient and cohesive system. MSW shouldn't be considered a homogeneous waste as it is a waste mixture. There must be waste sorting plants to effectively separate the waste as per its nature, thereby increasing the reusability of the materials. Depending on the kind of waste, the sorted waste should be sent to facilities like recycling plants, waste-to-energy plants, and landfills. The induction of more recycling and waste recovery facilities can help ease the pressure on the environment by providing material in the system. Solid waste must be considered an opportunity to generate energy or valuable material rather than trouble.

The sustainability of the circular economy-based MSW management system should be evaluated by advanced tools based on exergy as it can effectively predict the quality and quantity of the produce and inefficiencies in the processing system. Frequent analysis can help optimise the shortcomings of the individual components and improve the overall system. Therefore, a CE-driven waste management system must focus on rebuilding a stable economy, healthy environment, and happy society to achieve sustainability in a region or nation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sanjay Patel reports financial support was provided by Gujarat Council of Science and Technology.

Data availability

No data was used for the research described in the article.

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