

CHAPTER 5

Waste reduction and recycling initiatives for net zero

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5.1 Introduction

The term ‘waste reduction’ refers to methods and techniques designed to minimise the quantity of waste produced at its source. Instead of dealing with waste after it has been created, waste reduction focuses on preventing its formation. This includes designing products and production processes to generate less waste at the end of their life cycle and consume fewer resources throughout their lifespan. Efficient resource use can be achieved by promoting the economical use of water, energy, and materials in production processes. Raising awareness among consumers and encouraging them to purchase products with longer lifespans, while avoiding single-use items, are also essential strategies [1]. Recycling involves transforming waste materials into valuable products, adding value to the economy and the environment. It comprises three primary steps: collecting waste materials, sorting the collected materials, and processing them into new products.

The primary objective of recycling is to reduce environmental burdens and create valuable outputs by (1) collection: waste materials are gathered from various sources, such as industries, residential areas, and agricultural sites; (2) sorting: the collected materials are separated into groups based on their type, quality, and potential for recycling; and (3) processing: the sorted materials undergo production processes to transform them into valuable products. This recycling process often produces the same type of material from the waste (e.g. manufacturing plastic products from recycled plastic)—a key aspect of waste reduction and recycling. During recycling, some products may result in lower quality than the original waste materials (downcycling), while others may achieve higher quality (upcycling). Both industries and households should be encouraged to participate in recycling efforts. Municipal councils should provide kerbside collection services for residents, while industries can manage their recycling in-house or outsource it to a waste management company.

One crucial strategy for achieving net-zero goals is adopting a circular economy, where goods and materials are recycled, remanufactured, refurbished, and reused. Both waste reduction and recycling are essential tactics for achieving the global goal of net

zero, which involves balancing the greenhouse gas (GHG) emissions released into the atmosphere with those removed [2–4]. Reducing waste, particularly in the production of goods, directly lowers emissions associated with transportation, manufacturing, and disposal [3]. When waste is sent to landfills, it produces methane, a potent GHG. Waste reduction minimises the materials sent to landfills, mitigating methane emissions and reducing the overall carbon footprint [5]. Recycling is crucial in reducing emissions tied to extracting raw materials and manufacturing new products. For instance, recycling metals, plastics, and paper requires significantly less energy than producing these materials from virgin resources. A quantitative framework of global waste generation by material category, together with sectoral contributions to carbon dioxide emissions, is shown in Fig. 5.1.

Additionally, recycling both organic and inorganic waste decreases the amount of waste sent to landfills, further curbing methane generation. A key waste reduction strategy is using fewer materials in production processes. Individuals and companies can conserve critical raw materials, such as fossil fuels, minerals, and metals, reducing the demand for resource-intensive activities such as drilling, mining, and extraction. This conservation effort not only protects natural resources but also lessens associated emissions. Recycling transforms waste into valuable products that re-enter the supply chain, reducing the need for virgin resource extraction. This is especially significant for metals and rare materials, which have high environmental and carbon costs associated with their extraction and processing. While scholars have enriched the waste recycling sector by focusing on recycling methods, techniques, process optimisation, and input

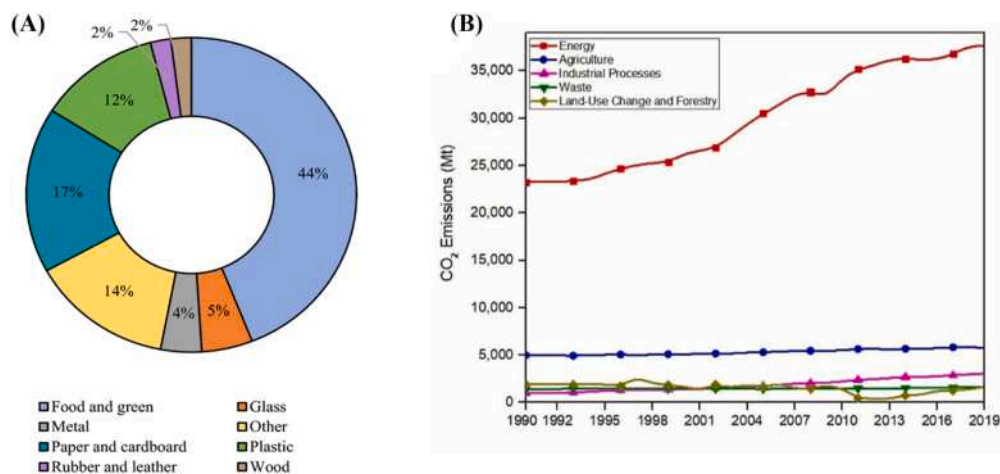


Figure 5.1 (A) Composition of global waste based on material types [6] and (B) contribution of major sectors for global CO₂ emissions from 1990 to 2019 [7].

and output analysis, a comprehensive study of problematic waste from various streams holds great significance. Such a study can impact net-zero targets by preserving valuable resources and reducing environmental harm by integrating waste reduction and recycling practices into production and consumption. Therefore this chapter outlines key strategies and approaches for reducing and recycling problematic waste to achieve a circular economy for net zero.

5.2 Waste minimisation techniques

5.2.1 Source-reduction strategies

Preventing waste generation at its source is more beneficial than treating it after it has been produced. This approach is embodied in the ‘Waste Minimisation’ concept, which advocates for techniques aimed at reducing waste generation [8]. Despite the application of various waste management strategies, industrial growth and urban expansion continue to drive an increase in waste production. Source-reduction strategies offer a solution by addressing the root causes of waste generation and complementing the implementation of other waste management technologies [9]. Unlike traditional waste management methods, which focus on managing waste after it has been generated, source-reduction strategies emphasise preventive measures implemented at the feedstock level, making them typically less expensive and less environmentally harmful than other waste management technologies. As a result, source reduction is often the preferred option for sustainable waste management.

5.2.1.1 Design for longevity and durability

Product design has become a critical focus for service providers and manufacturers, significantly influencing product longevity and durability. Effective design facilitates the implementation of circular strategies, such as repair, reuse, refurbishment, and remanufacturing, all of which help extend product lifespans [1]. A well-executed product design enhances longevity and durability, and maximises value retention within industrial systems [10]. By prolonging product lifecycles, environmental burdens are minimised through reduced waste generation. In this way, product design plays a pivotal role in achieving sustainability by linking product properties—such as longevity and durability—to extended lifetimes and environmental benefits. The more precise and thoughtful the design, the longer products will last, ultimately minimising waste and contributing to a more sustainable future.

5.2.1.2 Minimal packaging and product design

Packaging and product design are crucial to the supply chain, as they can reduce product loss and waste generation. Proper packaging and product design help extend the shelf

life of products, thus preventing waste [1]. Minimal or no packaging is desirable, as packaging becomes waste at the end of a product's life. However, packaging for sensitive products, such as medicine and certain foods, cannot be avoided. In such cases, minimal or eco-friendly packaging should be used to protect the product while reducing waste generation. Product design directly relates to packaging design and should enhance product properties while requiring minimal or sustainable packaging materials.

5.2.2 Process optimisation in manufacturing

Process optimisation is crucial to waste reduction because it enhances productivity, reduces resource consumption, and streamlines operations. Optimised operations improve labour, energy, and raw material management, reducing overproduction and surplus inventory, which may otherwise result in waste. Rework and defects are significant sources of waste, so optimising quality control techniques is essential to minimise them. By incorporating sustainability into process optimisation, eco-friendly products and methods can be adopted, reducing waste production and environmental impact. Manufacturing process optimisation fosters a culture of continuous improvement, where businesses regularly evaluate and enhance their operations to minimise waste gradually [11]. Lean manufacturing principles play a vital role in waste minimisation by focusing on value creation, continuous improvement, and efficiency [12]. This approach helps identify and evaluate each stage of the manufacturing process, distinguishing between value-adding activities and those that do not add value. Lean identifies seven categories of waste: overproduction, waiting, transportation, excess processing, defects, motion, and inventory [12].

By systematically identifying and eliminating these wastes, industries can optimise their processes. Lean promotes a culture of continuous improvement, where staff at all levels contribute suggestions for reducing waste and enhancing procedures. Material efficiency and waste audits work together, providing a comprehensive strategy for waste reduction. The goal of material efficiency is to use the fewest materials possible while achieving the desired results [8]. This includes minimising waste during manufacturing by optimising material use. Waste audits collect and analyse data to identify inefficiencies and opportunities for waste reduction. Based on this baseline data, industries can set measurable targets for waste reduction and monitor their progress over time. Industries can significantly reduce waste, lower costs, and enhance their sustainability efforts by focusing on material usage and conducting systematic waste assessments.

5.2.3 Consumer behaviour and waste prevention

Influencing consumer behaviour is one of the most effective strategies for minimising and preventing waste [4]. Educating consumers about the environmental impact of their

choices can encourage more eco-friendly purchasing decisions, such as opting for products with minimal packaging or those made from recyclable materials. Raising awareness about recycling, composting, and reusing also plays a significant role in reducing waste. Consumer demand for eco-friendly and sustainable products drives industries to reduce waste in their production processes. Promoting critical thinking among consumers helps reduce impulsive and excessive consumption, which lowers waste generation [13]. Waste minimisation can be significantly achieved through awareness campaigns, sustainable choices, and responsible consumption. Promoting sustainable consumption is crucial for reducing waste across various industries [13]. Sustainability labels guide consumers toward environmentally friendly products, which help reduce waste. Promoting long-lasting and repairable products reduces the need for replacements, lowering waste. Advocating for a culture that prioritises repair over disposal extends the lifespan of products and reduces waste.

By promoting conscious choices, supporting circular practices, and fostering a culture of sustainability, individuals and communities can lessen their environmental impact and contribute to a more sustainable future. Education and awareness programmes are crucial for waste reduction because they enable individuals to make informed decisions and adopt sustainable habits [13]. These programmes highlight the adverse impacts of waste on the environment and the economy, including resource depletion, pollution, and climate change. Teaching basic recycling and composting techniques can empower individuals to minimise waste in their homes and communities. Programmes can also promote deliberate consumption practices, such as making shopping lists and reducing impulsive purchases, which helps lower waste production. Education and awareness programmes are key to changing behaviour and fostering a waste-reducing mind-set. The impact of source reduction and process optimisation is presented in Table 5.1 and evaluated qualitatively in terms of efficiency, cost, environmental preservation, adoption patterns, and other relevant factors.

5.3 Recycling technologies and processes

In this section discusses various waste recycling technologies, emphasising the major technologies and processes for recycling plastic waste and metal waste, including electronic waste.

5.3.1 Plastic recycling techniques

There are three main types of plastic recycling techniques: mechanical, chemical, and biological. These are explained here with their pros and cons. Mechanical sorting, recycling, and reprocessing—mechanical recycling refers to physical treatments that generate secondary plastic materials from waste. Multiple steps are involved in mechanical

Table 5.1 Source reduction and process optimisation techniques, along with environmental impacts.

Technique	Description	Implementation examples	Efficiency gains	Cost implications	Key metrics	Environmental impact	Adoption rate	Time to implement	Lifespan (years)	Regional variations	References
Design for long-evity and durability	Products designed to last longer	Extended warranties, robust materials	Medium	Variable	Product lifespan	Reduced waste	Medium	6–12 months	10–20	Varies by region	[14–16]
Minimal packaging and product design	Reduction in packaging materials	Minimalist packaging, reusable containers	Medium	Low	Packaging weight	Reduced landfill waste	Minimum to high	3–6 months	5–10	Standard in many regions	[17,18]
Lean manufacturing principles	Streamlining production to reduce waste	Just-in-time production, waste audits	Medium	Medium	Waste reduction	Improved resource use	High	6–12 months	10–15	Widely adopted	[18,19]
Material efficiency and waste audits	Reducing material use and tracking waste	Waste audits, material efficiency programmes	Low to medium	Medium	Material usage	Reduced material waste	Medium to high	3–6 months	5–10	Varies by industry	[20,21]

recycling, such as selection, acquisition, heat treatment, extruding, and re-compounding [22,23]. Plastics Europe defined mechanical recycling as ‘a technology by which secondary raw material is generated from plastic waste without altering the main structure of the component’. Recycling requires melting, shredding, or granulating waste plastics [24]. Nevertheless, it can only work with single-polymer plastics such as polystyrene (PS), polypropylene (PP), polyethylene (PE), etc. In Europe, mechanical recycling is the most commonly applied method for recycling postconsumer packaging plastics, with more than 99% of waste packaging plastic being recycled through this process [25].

Some techniques for sorting and separating critical parts from plastic waste are wet gravity separation, ballistic separation, zigzag separation, electrostatic separation, froth floatation, and air tabling. Sensor-based separation methods, such as near- infrared (NIR) and colour sorting are also available for plastic waste. Recently, the Massachusetts Institute of Technology developed a ‘RoCycle’ system that utilises in-hand sensors to detect objects, such as plastics [26]. The design of the robotic hand might include data on polymer composition, plastic types, and the categorisation of plastic waste according to thermal stress and degradation. The collected polymers are sorted, melted, and either re-granulated or moulded into a new shape [27]. Mechanical recycling is characterised by an open loop and a closed loop, where in the first one, the plastics, mainly polyethylene terephthalate (PET) bottles, are converted to fleeces or duvets for low-value applications, while in the second process, PET bottles are turned into PET bottles with similar material or equivalent properties [28]. Veolia's waste plastic (mechanical) recycling process is presented in Fig. 5.2.

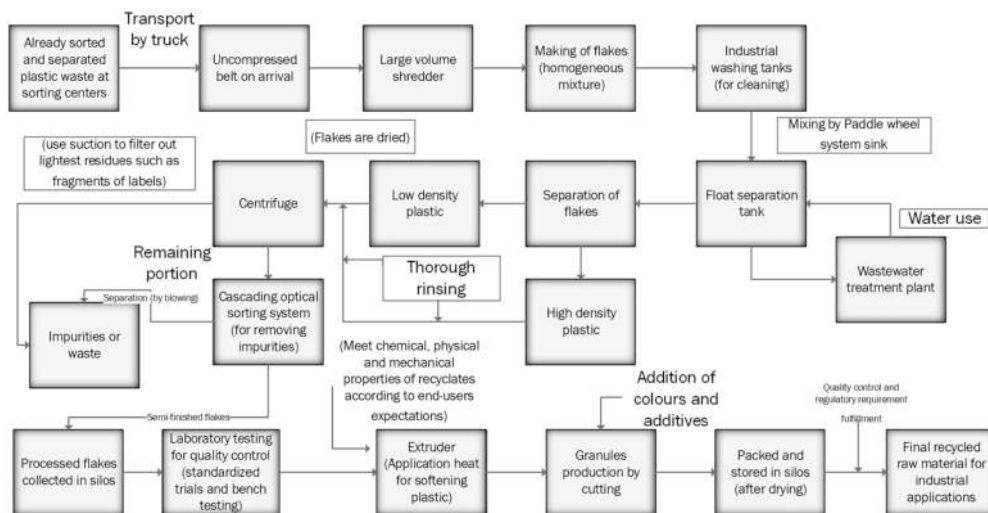


Figure 5.2 Waste plastic mechanical recycling process flow diagram of Veolia [29].

The major obstacles of the ME include lower efficiency in sorting and separation, the inability to handle mixed plastics, low-quality recyclates from recycling, legislative standards, new market development for recycled products, and a lack of investment. In addition, the diversity and deterioration of plastic waste create serious problems because, in several cases, the original mechanical properties and characteristics are deformed due to the evolution of mechanical stress during the plastic production process. Due to the diverse conditions, suitability, and high energy consumption, polymer-based plastic recycling often poses a critical challenge in the processing line. Additionally, the energy used in the process comes from nonrenewable energy sources, which generate more significant process emissions.

Moreover, one of the leading technological obstacles in mechanical recycling is the development of new technologies that can eliminate volatile organic compounds to enhance the quality of recovered plastics [30]. The technical, chemical, and physical characterisation of plastic waste is required to optimise Faraca and Astrup's recycling process. Furthermore, controlling recycled plastic and product certification are critical elements of waste plastic separation technologies [31]. The cost of recycling and inadequate mechanical recycling capabilities dealing with additives are significant barriers to mechanical recycling [32]. Developing a multidimensional value assessment tool (based on material properties and design characteristics) is required for quality improvement in the sorting process [33]. Figs. 5.3 and 5.4 represent plastic recycling techniques. However, Table 5.2 shows the technology-specific main limitations of mechanical and chemical recycling.

Chemical recycling converts polymers into simpler chemical structures or chemicals that can be used in various industrial applications and/or in the production of plastics and petrochemicals. This process is known as chemical recycling [44,45]. Manufacturers of chemicals and gasoline are directly involved in this type of recycling [44]. Chemical recycling methods include gasification, hydrogenation, and pyrolysis Fig. 5.5 [46]. The importance of chemical recycling is gaining popularity due to the rapid market shift, high resistance to plastic, and the fundamental characteristics of the open-loop recycling concept [47]. The primary industry that may utilise the products of the chemical recycling process is the food packaging industry [48]. The international research community focuses critically on the use and recovery of catalysts.

Due to resource and energy-sensitive processes, long reaction times, complex operating processes, and highly corrosive reagents, metal-based catalyst development is one of the research agendas [49] which should also be considered by the researchers. On the other hand, in developing countries, the development of chemical recycling-based biorefineries requires an environmental, technical, financial, and social analysis through life cycle assessment (LCA) for various types of plastic waste [50]. However, there is a limited understanding of the environmental performance of cracking in chemical recycling and upcycling [51]. During the thermal degradation process, combustible gases,

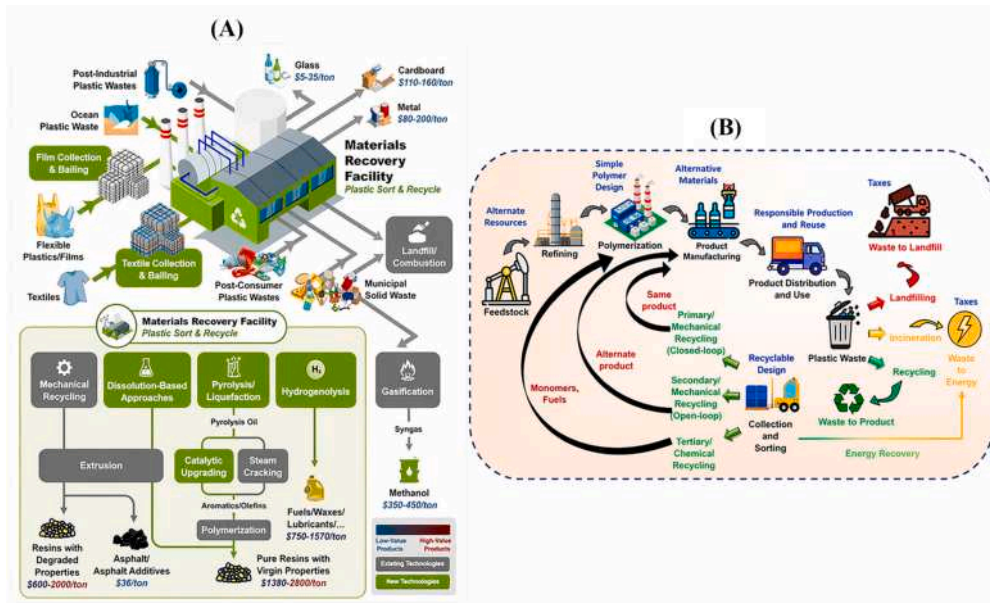


Figure 5.3 Overview of the plastic recycling technologies: (A) existing and novel technologies along with their outputs [34] and (B) route of the plastic life cycle with potential solutions to achieve sustainability [35].

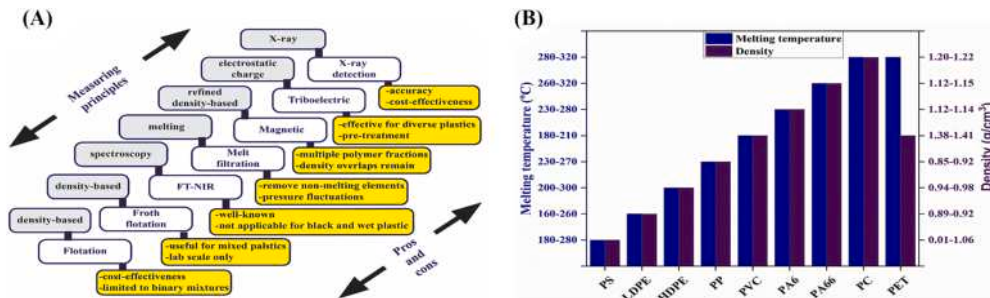


Figure 5.4 (A) Sorting techniques used in mechanical recycling methods along with their measuring principles (grey background) and characteristics (yellow background) [23]. (B) Parameters for plastic waste recycling; range of processing temperatures and densities for common plastics [36-39].

Table 5.2 Limitations associated with mechanical recycling and various techniques used in chemical recycling methods.

Recycling methods	Techniques	Limitations	Common waste processed	Output	References
Chemical	Chemolysis	Lack of cost-effectiveness for high volume, limited to only condensation polymers	Polyethylene terephthalate (PET)	Feedstock	[23]
	Pyrolysis	Complex reactions, lack of cost-effectiveness for high volume, less resistance for polyvinyl chloride (PVC), absence of suitable waste supply	Mixed polyethylene (PE)/polypropylene (PP)/polystyrene (PS), multilayer packaging, polyurethane (PU), automotive shredder residue	Gas, liquid (fuel), char, feedstock	[38]
	Fluid catalytic cracking	Difficulties in deactivating catalyst, existence of inorganics, absence of require reactor technology	PE, PS, PP, PVC, PET	Fuel, commodity and fine chemicals	[39]
	Hydrocracking technologies	High cost of H ₂ , operation, investment	Mix plastics	Naphtha feed	[23]
	Hydrogen technologies integrated hydrolysis and hydroconversion (IH2) process	Requirement for further research	Mix plastics, organic material (cellulosic fractions, wood and biomass)	Liquid hydrocarbons (fuel)	[40]

Mechanical	Katlytische depolymerisation (KDV) process	Lack of understanding of underlying chemistry and technical information	PET, PP and lignocellulose	Directly usable liquid fuel (diesel, kerosene and petroleum)	[41]
	Gasification	Presence and considerable presence of noxious nitrogen oxides, specific drawbacks of air	All types of plastics along with organic materials	Syngas (mixture of hydrogen, carbon monoxide, small amount of methane, carbon dioxide and hydrocarbons)	[42]
		Thermal-mechanical degradation, presence of complex mixture, and finally, miscibility of polymer blends	All types of thermoplastics, particularly PET, PP, PE, acrylonitrile butadiene styrene (ABS) and PS	Original products (close loop) or lower value items (open loop)	[43]

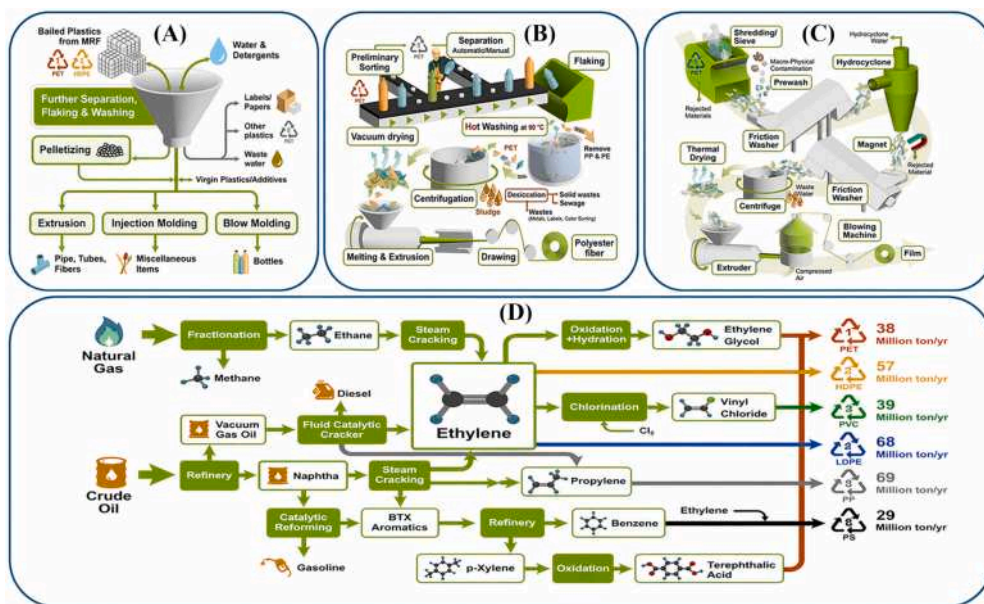


Figure 5.5 Plastic recycling processes for various common waste: (A) mechanical recycling of solid plastic waste, (B) process flow chart of polyethylene terephthalate (PET) bottles recycling, (C) industrial recycling process of polyethylene films, (D) manufacturing process of common plastics (PET, high-density polyethylene [HDPE], polyvinyl chloride [PVC], low-density polyethylene [LDPE], polypropylene [PP] and polystyrene [PS]) [30,34].

energy, and/or molecules are produced as multistream output. The pyrolysis process can produce a clean, high-calorific-value gas from a wide range of biomass and waste streams [47]. The advantages of pyrolysis can be categorised into three different segments.

Using residual chars and eliminating the need for flue gas are the primary operational benefits; from an environmental perspective, the additional benefits include decreased landfilling and lower CO₂ and GHG emissions. The main advantages of the pyrolysis process are the production of heat, simple operating conditions, and the production of valuable products [47]. In biological recycling, microorganisms such as fungi and bacteria can break down natural and synthetic plastics [52]. Soil condition determines the optimal growth conditions and biodegradability of plastics, as potential substrates for heterotrophic microorganisms [36]. PET biodegradation using an enzymatic approach is a commercially feasible recycling technique [37]. Combining microbiology and pyrolysis is the unconventional route to convert nonbiodegradable plastic such as PS, PE, and PET to biodegradable products such as polyhydroxyalkanoates [53]. However, process time, operational cost, resource availability, and energy consumption are some limiting factors and technical barriers to the biological recycling process. Maintenance of

pressure and temperature, crystallisation, filtration, and distillation are some of the major process requirements of recycling.

5.3.2 Metals and e-waste recycling processes

For metal recycling, there are three conventional pathways: (1) pyrometallurgy, (2) hydrometallurgy, and (3) biometallurgy. In pyrometallurgy, the waste-containing metals are thermally isolated from the nonmetals at high temperatures through melting and/or reduction. In hydrometallurgy, the waste materials are digested and leached, and the metals are recovered by deposition from the leaching solution. In biometallurgy technology, waste materials are recovered and interact with microorganisms, leachates, and metals. In addition to these individual pathways, combined processes that integrate two or more of these technologies are often employed. These hybrid approaches improve efficiency and effectiveness in metal recovery and recycling. Metal recycling offers several advantages, chief among them being the potential to reduce the extraction of virgin ores, thereby extending the life of these resources. When recycled materials are used instead of virgin materials, the environmental impact of metal production is significantly reduced, and recycling is typically far more energy-efficient than mining [54]. Depending on the metal and type of scrap, recycling can reduce energy use by a factor of 10–20, or sometimes even less than that [5].

Ecotoxicity concerns can also arise from the disposal of nanoparticles containing metals. Modern solid-waste incinerator technology can effectively remove toxic nanoparticles from flue gases. However, this heat-treatment technology does not alter the properties or structure of the nanoparticles, resulting in their disposal in landfills [55], and similar issues arise during the recycling process. After collection, postconsumer metals undergo a series of preprocessing steps, including disassembly, chemical and physical separation, and various sorting techniques (e.g. manual, optical, magnetic). Virgin material processing typically occurs on a large scale, supported by historically low energy costs. In contrast, recycling often operates on a smaller scale and is more labour-intensive. Consequently, substantial recoverable material is lost, and financial returns are often insufficient to justify investment in advanced ‘sense and sort’ technologies. After preprocessing, materials are sent to a thermochemical facility, such as a smelter, for end-processing. Typically, primary smelters handle this stage, while facilities such as EAFs used in the steel industry and specialised smelters for precious metals, copper, and certain speciality metals focus on processing secondary metals. Currently, at least half of the metals face greater recycling challenges due to the inefficiency of the recycling process itself.

5.3.3 Innovations in recycling technologies

Waste is utilised in a nonconventional way to divert from landfilling and prevent the loss of resources. One example is that plastics are used in road construction due to their

good binding properties at high temperatures [39]. Technological advances are facilitating it in different ways. During concrete manufacturing, plastic waste can be utilised as partial aggregates. Moreover, plastic fibre can be used for reinforcement instead of standard steel [56]. Fly ash and recycled plastics could be used to create fire-retardant composites for various applications [29]. In metal recycling, innovations such as microwave- and plasma-assisted eutectic solvent leaching and supercritical fluid extraction of metals from waste have garnered significant attention from researchers [57]. In the area of chemical recycling, researchers have developed and highlighted various innovative technologies, including ultraviolet light for degradation, ultrasound-based recycling, microwave-assisted heating, cold plasma, supercritical fluid-based extraction methodologies, electrodeposition, and high-pressure-based technologies for recycling plastics and metals [58]. Many researchers have developed precipitation and solvent-targeted recovery technologies that can recover different metals, such as Cu, Co, Al, and Ni, as well as various polymers (PET, ethylene vinyl acetate, and PE), from mixed waste, resulting in 100% recoverable materials and a cost-efficient process when compared to virgin materials [53].

Some chemical recycling processes and electrodeposition treatments for multilayer polymers and metals include gasification, hydrogen technology, catalytic cracking, pyrolysis, chemolysis, and others [59]. A special solvent was developed to separate different layers in blister packets and food wrapping. British Petroleum designed the Infinia recycling process to transfer opaque PET plastic scrap into valuable feedstocks without compromising quality [60]. An emerging waste management approach is replacing conventional oil-based plastics with bio-based materials, such as bioplastics derived from bio-waste, plants, and other renewable sources. Bio-based materials are environmentally friendly and possess sustainable physical and chemical properties, making them attractive for various applications, including packaging, medicine, pharmaceuticals, electronics, and batteries [61]. However, due to high production costs and slow manufacturing rates, industries currently produce and utilise only a limited range of biopolymers. Future research should focus on enhancing the properties of bioplastics and developing new, economically viable production technologies. Some advancements are already evident—for example, the medical industry has adopted bio-based materials for implants and drug delivery systems, while the cosmetics industry is increasingly incorporating them into its products [62,63]. Table 5.3 describes different recycling technologies' efficiency, impact, and recycling rates.

5.4 Waste-to-energy conversion methods

Waste-to-energy (WtE) technologies include several waste treatment processes that convert different types of waste into energy, including electricity and heat. These

Table 5.3 A detailed comparison of recycling technologies and processes.

Technol- ogy	Materi- al type	Process descrip- tion	Recovery rate (%)	Energy con- sump- tion (kWh/ ton)	Cost per ton (USD)	Efficiency (%)	Contamin- ation rate (%)	Key metrics	Environ- mental impact	Lifetime of equip- ment (years)	Adoption rate (%)	Region- al varia- tions	References
Plastics recy- cling tech- niques	Plastics	Mechani- cal recy- cling, che- mical recy- cling	50–90	300–500	200–400	70–85	5–10	Recycled plastic quality	Reduced plastic waste	10–15	55–65	High in devel- oped regio- ns	[1,64,65]
Metals recy- cling pro- cesses	Metals	Smelting, electro- lysis	90–95	250–450	150–300	85–90	2–5	Metal purity	Reduced metal waste	15–20	60–70	Comm- on globa- lly	[55,57]
Mechanic- al sorting tech- nologi- es	Mixed waste	Separation using con- veyor belts and screens	80–90	100–200	50–100	75–80	10–15	Sorting efficiency	Reduced sorting costs	7–12	50–60	Variable by region	[66]
Robotics and artificial intelli- gence (AI) sorting	Mixed waste	Automat- ed sorting using AI and roboti- cs	90–95	200–300	200–500	85–90	5–10	Sorting speed	Improved sorting accura- cy	5–10	40–50	Emergi- ng tech- nolo- gy	[67–69]

(Continued)

Table 5.3 (Continued)

Technol- ogy	Materi- al type	Process descrip- tion	Recovery rate (%)	Energy con- sump- tion (kWh/ ton)	Cost per ton (USD)	Efficiency (%)	Contamin- ation rate (%)	Key metrics	Environ- mental impact	Lifetime of equip- ment (years)	Adoption rate (%)	Region- al varia- tions	References
Chemical recy- cling advanc- ements	Plastics and orga- nic waste	Depolym- erisa- tion, advanc- ed che- mical pro- cesses	60–80	400–600	300–600	70–80	5–10	Recycled material purity	Reduced che- mical waste	5–10	35–45	High in resea- rch labs	[70,71]
Bio-based and biode- grad- able mate- rials	Various	Use of bio- based or biode- grad- able polym- ers	50–70	150–250	100–200	60–70	2–5	Biodegradab- ility rate	Reduced landfill waste	5–10	30–40	Increasi- ng new pro- ducts	[61,72–74]

technologies can process a diverse range of waste streams, including semisolid materials such as thickened industrial sludge and liquid wastes such as domestic sewage.

5.4.1 Common technologies

Key mentionable WtE technologies include incineration, gasification, pyrolysis and anaerobic digestion (Fig. 5.6). The incineration process involves direct combustion of waste and/or refuse-derived fuel between 750°C and 1100°C in an oxygen-rich environment. In gasification, the partial oxidation of waste (e.g. wood waste, agricultural residues, sewage sludge, and plastic waste) is performed at temperatures between 800°C and 1200°C. Under the controlled oxygen level, this process generates synthetic gas that can be further combusted or converted into chemical feedstock. As a thermal degradation process, pyrolysis breaks down waste (e.g. wood waste, agricultural residues, sewage sludge, and plastic waste) in an oxygen-free environment at temperatures ranging from 300°C to 1300°C [78]. The process produces a liquid fuel that can be used for combustion or converted into a chemical feedstock. The last one is a biological process in which anaerobic microorganisms degrade organic waste in the absence of oxygen [79].

Wastes include separated organic municipal solid waste, food waste, animal and/or human excreta, liquids, and sludges, which are commonly treated in this process to generate biogas and digestate. The former can be used as fuel for power generators, and the latter can be used as a soil conditioner or dewatered and utilised as a low-calorific-value refuse-derived fuel. In gasification, plastic and other organic waste (i.e. bio-waste, textiles, woods, etc.) are gasified by reacting with gasifying agents (such as air, steam, and oxygen) at high temperatures (between 500°C and 1300°C) to produce synthesis gas or syngas, which can then be used to produce a variety of chemicals including fuel for fuel cells to produce electricity, with partial oxidation producing a gaseous mixture of methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2), and carbon monoxide (CO) [42].

Gasification is conducted at atmospheric pressure and a temperature range of 700°C–1500°C in the presence of steam, air, and oxygen. As part of chemical recycling, pyrolysis and gasification are the most popular plastic waste recycling technologies due to their economic advantages, robustness, and flexibility (Lopez, Artetxe, Amutio, Alvarez, Bilbao, and Olazar) [80]. In addition, more characterisation of the plastic waste is required to develop optimal processes for PET, polyvinyl chloride, PS, PP, low-density polyethylene (LDPE), and high–high density polyethylene [81]. The limited use of landfilling reduces greenhouse gas (GHG) emissions, including CO_2 , which is also a key advantage of pyrolysis and gasification [82]. Gasification process can be utilised with biomass, coal, and plastic waste mixtures [83,84]. Supercritical gasification (SCG) and carbonisation are the main dominant research areas, along with hydrothermal

liquefaction, which has both advantages and disadvantages [81]. For syngas and high-calorific-value fuel gas production, SCG is particularly useful [42].

5.4.2 Challenges

Several challenges are associated with WtE conversion, such as determining the exact optimum values of biodiesel properties. Therefore there is a need for LCA and energy-based analysis that considers the composition of biodiesel, its impact on fuel properties, and polymer dissolution phenomena [85]. However, due to increased capital investment and high operating and maintenance costs, communities often do not accept social resistance to WtE conversion plants because of the different plastic additives that are detrimental to health [86]. The process efficiency of energy conversion technology, which focuses on air pollution and residual ash management, should also be optimised in the WtE plant [87]. Table 5.4 illustrates different WtE conversion methods and their impacts.

5.5 Circular economy and resource efficiency

5.5.1 Perspectives of product design

Design for recycling is one of the critical aspects for high resource efficiency and a better material supply chain. Extended producer responsibility (EPR) should provide specific roles for major polymer manufacturing players in the supply chain, including innovation in waste management systems. From a product design perspective, plastic and metal processors should be provided with adequate financial and technical support in cooperation with material manufacturers (plastics and metals), equipment manufacturers, and end-use sectors such as packaging, infrastructure, automotive, electronics, battery, and agriculture. Future researchers should focus on how individual sectors, such as automobiles, electronics, and construction, deal with waste management and resource recirculation issues within their respective industries. As the production of high-density polyethylene (HDPE), LDPE, and PP are the highest among the polymers, the main sectors should develop product designs that are better recyclable and less likely to get contaminated. Furthermore, metal-containing additives (e.g. fillers) at the plastic production stage should be limited—however, the lack of quantitative data on the substances and contaminants limits associated with reprocessing technology [97].

5.5.2 Prospective initiatives

To mitigate the impact of waste on human health and the environment, and to achieve a circular economy through collection, segregation, and recycling, a collaborative

Table 5.4 A comparison of waste-to-energy conversion methods.

Method	Description	Energy output (MJ/kg)	Emission levels (g CO ₂ /kg)	Cost per MWh (USD)	Efficiency (%)	By-products	Key metrics	Environmental impact	Equipment lifespan (years)	Adoption rate (%)	Regional variations	References
Incineration and energy recovery	Burning waste to generate energy	10–15	800–1200	50–80	70–80	Ash, flue gas	Energy recovery rate	High CO ₂ emissions	15–20	60–70	Common in many countries	[88–90]
Anaerobic digestion and biogas	Organic waste converted to biogas	20–30	100–300	40–60	60–70	Digestate, biogas	Biogas yield	Reduced methane emissions	10–15	50–60	Widely used in agriculture	[91–94]
Gasification and pyrolysis	Conversion of waste to synthetic gases	15–25	200–400	60–100	65–75	Syngas, char, bio-oil	Gas purity	Lower hazardous waste	15–20	40–50	Emerging technology	[95,96]

partnership has been established among various countries. For example, United Nations Development Programme (UNDP) India, Hindustan Coca-Cola Beverages Private Limited, Hindustan Unilever Limited, HDFC Bank and Coca-Cola India Foundation aiming to improve the socio-economic condition of the waste pickers (Safai Sathis) and managing 85,000 million tons (Mt) plastic waste within the project duration 2018–24 [98]. The main objectives of the initiatives are to develop a model of socio-technical that transforms the formal sector into the informal sector, establish a pilot material recovery facility, upgrade the socio-economic status of the waste collectors (via a socio-technical model), implement technical knowledge, digital governance, and accountability in the value chain of waste [99]. Using digital technology across all materials value chains, all the stakeholders could be integrated, which would later be beneficial for tracking the flow of waste into the supply chain, starting from the collection point to the recycling location and, most notably, in a digital market [100]. Also, implementing the right scaled technology (small, medium, or large) fit for the purpose is essential to recycle complex wastes, such as e-waste and batteries, multilayered packaging, etc. [101]. Table 5.5 describes different strategies for achieving a circular economy for waste materials and their impacts.

5.6 Policy and regulatory frameworks for waste management

Different countries have national waste policies aligned with global waste management strategies and strategies for dealing with waste should consist of the following elements: sector-specific norms, standards, and procedures; compliance and enforcement; environmental liability by self-responsiveness; green public procurement; taxes and levies; fees and user charges; subsidies/incentives; product labelling; monitoring and feedback system, etc. Considering influencing factors, for example, geographical location, weather, demography, urbanisation, product consumption scenario, infrastructure and technological capacity, appropriate policy should be adopted by relevance and properly assessing the focused area [112].

5.6.1 Global practices

The United Nations Environment Programme's Global Waste Management Outlook 2024 report provides guidelines on waste management strategies and outlines the responsibilities of stakeholders. The report warns that without urgent and effective initiatives, the cost of waste management is expected to double by 2050. International agreements such as the Montreal Protocol and the Kyoto Protocol advocate for reducing GHGs emissions, complementing efforts to address waste-related

Table 5.5 Circular economy and resource efficiency along with regional variations.

Strategy	Description	Implementation examples	Resource savings	Economic impact	Key metrics	Environmental impact	Adoption rate	Regional variations	References
Design for disassembly and reuse	Designing products for easy disassembly	Modular designs, recyclable components	Medium to high	Variable	Product recyclability	Reduced material waste	Medium	Varies by industry	[102–104]
Closed-loop systems	Reusing materials within the production cycle	Closed-loop manufacturing processes	Medium to high	Medium	Resource efficiency	Reduced production waste	Medium to high	Varies by industry emerging in some sectors	[105]
Extended producer responsibility	Producers take responsibility for product lifecycle	Take-back programmes, recycling initiatives	High	Variable	Producer involvement	Increased recycling rates	Low to medium	Standard in many regions	[106,107]
Industrial symbiosis and waste exchanges	Collaborative use of resources and waste	Waste exchanges, shared resource systems	Medium to high	High	Resource sharing	Reduced industrial waste	Low to medium	Varies by industry	[108,109]
Product-as-a-service models	Shifting from ownership to service-based models	Leasing and servicing products	Medium to high	Medium	Product life-cycle	Reduced product waste	Low to medium	Emerging in some sectors	[110,111]

environmental challenges. The Basel Convention commits participating countries to reducing, controlling, and reusing hazardous waste, such as electronic and battery waste, while ensuring its safe disposal. Similarly, News Corp's Global Waste Management Policy emphasises the 4Rs—rethink, reduce, reuse, and recycle—for efficient waste management practices. In different countries, dedicated authorities have prepared guidelines and policies for recycling. For instance, Australia's National Waste Policy aims to significantly reduce waste generation, targeting 80% reduction in specific waste streams by 2030. It also focuses on increasing the use of recyclates and phasing out single-use plastics, with some states implementing bans as early as 2019.

The People's Republic of China (2015) National Development and Reform Commission was one of five departments that jointly released the 'Technical Policy for Electric Vehicle Power Battery Recycling and Utilisation (2015 Edition)' to control exhaust emissions and set a recycling rate limit for metals. However, the recycling indicators are inconsistent due to the different sources of waste materials. Furthermore, the recycling policy serves as a guiding principle at the macro level, which means that not all waste materials are specifically targeted for recycling. An initiative was launched for EU member states to adopt a zero waste hierarchy by following proposed guidelines for existing and new policies on waste prevention and product design. The European Waste Directive establishes a priority framework for waste management, encompassing prevention, preparation for reuse, recycling, recovery, and disposal of waste, with targets aimed at addressing GHG emissions and promoting decarbonisation [112]. Similarly, Malaysia has also adopted EPR practice for household e-waste (Fig. 5.7). Table 5.6 describes different policy and regulatory frameworks for waste management.

5.7 Economic aspects of waste reduction and recycling: target-net zero

Though the market size of global waste holds a significant amount (Fig. 5.8), the economic value of the materials present in the waste and the volumes involved are essential factors that influence recycling efficiency. Most metals and plastics currently being recycled are those used in large quantities, enabling economies of scale. Metals such as nickel, lead, zinc, copper, aluminium, and steel are found in relatively pure forms and can be easily remelted [57]. Their recovery/recycling rates exceed 50%, the products they use often have lifespans of several decades [57], and the recycling infrastructures for these metals are well-established. In some cases, the recycling rate of plastics is more than 70%. At the other end of the spectrum, valuable materials are used in trace amounts, 'specialty' materials are incorporated to enhance the performance of high-tech products such as solar cells, jet engines, and consumer electronics [3].

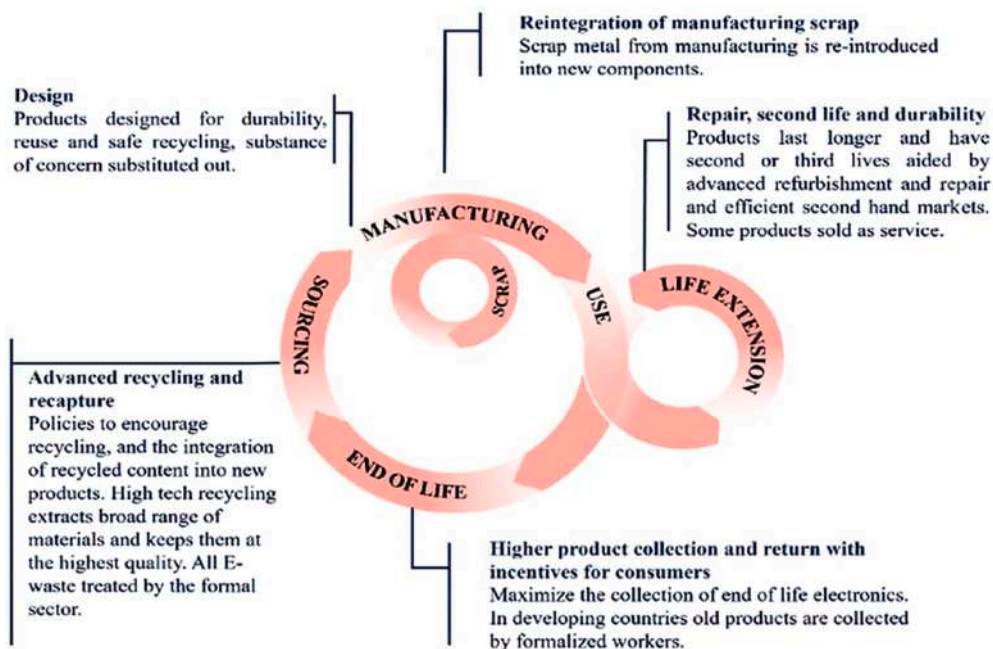


Figure 5.7 Circular vision for household E-waste management in the Malaysian context adopting extended producer responsibility practice mandatorily for manufacturers [113].

These applications require significant material mixing and complex separation technologies, and often face unfavourable economics due to the small volumes involved. The use of speciality metals is increasing, and as many electronic devices have short lifespans, end-of-life (EoL) losses will rise rapidly unless better recycling technologies are developed [101].

5.7.1 Recovery of commodity materials: metals

With the help of a circular economy, recycling can achieve carbon neutrality and ensure resource availability [55,119,120]. Steel—in steel production, carbon in the form of coke from virgin sources is utilised to reduce iron ore in furnaces, resulting in 1.6 to 3.1 tons of CO₂ emissions for 1 ton of steel manufacturing [121]. Additionally, fossil fuel-based energy with high temperatures for steelmaking (1100°C to 1500°C) contributes further to CO₂ emissions. To reduce CO₂ emissions, it is recommended to adopt electric arc furnace (EAF) ‘minimills’ powered by emissions-free electricity, as well as efficiency improvements such as top gas recovery, innovative techniques such as ultra-low CO₂ direct reduction, transition to alternative fuels for process heat, and demand reduction

Table 5.6 Policy and regulatory frameworks for waste management.

Policy type	Description	Target goals	Implementation examples	Effectiveness	Compliance	Key metrics	Environmental impact	Adoption rate	Time to enforce	Lifespan (years)	Regional variations	References
Global waste management policies	International agreements and conventions	Reduce global waste from all kinds of waste streams	Basel Convention, Stockholm Convention	High	High	Global compliance	Improved global waste management	High	1–3 years	Ongoing	Varies globally	[114,115]
National and regional regulations	Local and national waste reduction standards	National waste reduction targets	Australian National Waste Policy	High	High	National compliance	Increased recycling rates	High	1–15 years	Ongoing	Common in many countries	[116]
Local government initiatives	Waste and sustainable materials strategy in NSW	Waste reduction goals	Strategic direction for waste in NSW, Australia	High	High	Local programme success	Improved local waste management	Medium to high	1–5 months	Ongoing	Varies by city	[117]
Waste reduction targets and standards	Specific targets for waste reduction in the EU	Targets 60% reuse and recycling of municipal waste by 2030	Zero-waste programmes, landfill bans	Medium to high	High	Target achievement	Reduced landfill use	High	1–15 years	Ongoing	Varies by region	[118]



Figure 5.8 Market size of different waste streams in a particular year: (A) solid waste (2026), (B) e-waste (2023), (C) plastic waste (2023), (D) hazardous waste (2023), (E) automobile shredded waste (2025) and (F) waste-to-energy streams (2023). The global waste market made \$435 billion in 2023 [112].

through improved engineering practices. For example, transitioning to ultra-high-strength steel in vehicle manufacturing globally could prevent approximately 160 Mt of CO₂ emissions annually. However, EAF production is currently limited to approximately 30% of global demand due to the limited availability of scrap steel feedstock [121].

While these strategies reduce emissions, they do not eliminate them. Alternative reductants, such as charcoal (from biomass) and hydrogen, offer additional potential. Historically, charcoal was widely used until the 18th century, and the Brazilian steel industry has increasingly employed it to reduce fossil CO₂ emissions [122]. However, producing 0.6 tons of charcoal per ton of steel requires 0.1 to 0.3 hectares of eucalyptus forests [123]. Meeting the projected charcoal demand of the steel sector would require hundreds of millions of hectares of fertile land, and the resulting land-use changes could generate emissions that surpass reductions in fossil fuel usage, as observed in Brazil. Hydrogen, another alternative reductant, could also play a role but may compromise steel quality, as carbon contributes to steel's strength and desirable properties. Despite the challenges, capturing and storing process CO₂ emissions offers promise. This approach has been successfully demonstrated, particularly in configurations such as top gas recycling blast furnaces, where the concentrations and partial pressures of CO and CO₂ reach approximately 40%–50% and 35% by volume, respectively [124].

Copper is considered a strategic metal with a long history of being associated with the needs of contemporary societies. As a result, it is improbable that there will be no copper in this century. The utilisation scenario of these mineral assets is increasing daily due to rapid industrial and population growth, creating resource shortages in regional

and global economies [125,126]. This is particularly true for copper, as it is difficult to replace its distinct electrical properties with those of another metal [127]. Over time, the comparatively constant interior chemistry helps to preserve copper's durability. Due to its wide range of applications, copper demand has increased in the modern high-tech world [128,129]. Increasing the depth of copper mines may result in an unsustainable supply and likely increase carbon emissions [130]. Mining phases are a significant source of carbon emissions, and processing phases such as refining and primary smelting also emit carbon. The production processes associated with copper mining are recognised to be the most GHG-emitting and energy-intensive operations [131]. According to evaluations, the normal range of carbon intensity per ton of copper production is 1–9 t CO₂-eq [132]. An estimate of the EoL recycling rate suggests it exceeds 50% [133,134]; however, actual recycling rates worldwide are lower than this projection, exacerbating supply shortages. As a more practical subdivision of the circular economy agenda, secondary production from anthropogenic circularity is a viable and promising approach to addressing carbon emissions and resource demand in many nations [134,135].

Additionally, enhancing the efficiency of metallurgical recycling would also reduce energy usage and environmental harm. Compared to other metals, copper has an additional benefit regarding ordinary recyclability: it can undergo multiple recycling cycles with a long-term, somewhat consistent impact on its internal structure [136]. As a result, copper is one of the most recycled metals at present [137]. Although ore grades will probably continue to decline in the coming generations [138], copper's recycling capacity helps balance the pace of consumption. Furthermore, given the right circumstances, secondary production might save about 80% of the energy used in original production [139]. A certain amount of prior research has been conducted on the demand trend for copper and global copper production [138,140]. For example, global demand for copper was projected based on recycling scenarios and socio-economic factors (i.e. speculative conditions such as recycling rates of 90% and 70%) [126]. They discovered that before 2100, the total demand for copper would exceed the amount of resource-carrying capability.

Additionally, they have expressed that urban mining is a viable strategy for boosting resource recovery and that further development is necessary for regional assessments to account for variations in copper demand between regions fully. Dwindling ore grades led to a significant rise in energy consumption among Chilean copper miners between 2001 and 2017 [138]. Additionally, they stated that the decline in ore grade would likely continue, which might lead to higher energy use and carbon emissions from copper mining. In light of this, this research aims to create thorough scenarios that investigate how EoL copper recycling relates to emissions, assembly and resource-carrying capacity from a local to a global extent. Cobalt demand has increased dramatically in recent years due to the ongoing expansion of the energy industry [141]. Since 2007, cobalt recycling has the potential to increase feedstock availability and lower emissions of pollutants.

Nevertheless, the current state of cobalt recycling is unsatisfactory due to issues with dispersed resources, irregular procedures, and limitations on its environmental impact. By 2030, yearly electric vehicles (EV) sales must make up at least 35% of worldwide vehicle sales to support a net-zero transition and meet the Paris Agreement aim of lowering the global mean temperature rise. This requires an estimated 1.2 million tonnes of cobalt [142].

Furthermore, EV batteries must be durable and safe [74], and by 2030, used battery collecting rates must rise to at least 70%. The current recycling rate is approximately 32%, which is far lower than the required rate to meet anticipated cobalt supply shortages and is not economically feasible [142]. The most practical secondary Co extraction approach is recycling waste-containing Co, such as batteries. However, the criteria are not always met by the recovered cathode materials. Some studies have discovered that extracting cobalt from waste is quite beneficial. According to research, cobalt recycling requires 46% less energy than mining [143]. Water consumption from cobalt recycling is 40% lower than from primary manufacturing. Recycling reduces GHG emissions by 59%. Some researchers have found that cobalt extraction from waste sources is highly advantageous. Researchers argue that cobalt recycling results in 46% lower energy consumption compared to primary production. Cobalt recycling results in a 40% reduction in water usage compared to primary production. Recycling contributes to a 59% reduction in GHG emissions associated with the Co flow [144].

Precious metals are used in small quantities but have high economic value. Although their value strongly incentivises recycling, their EoL recycling rate is only about 60% [57]. While industrial catalysts and traditional jewellery recycling achieve high rates, collecting and recycling rhodium, palladium, and platinum from automotive catalysts is more challenging. In developed nations, collection rates for these metals often hover around 50%, mainly due to the export of used cars to developing countries with inadequate recycling infrastructure [145]. The dismal 5% to 10% recycling rate for platinum metals from electronics is influenced by similar factors [146]. Informal recycling and low-tech processing drastically reduce the amount of precious metals that can be recovered from consumer goods in developing nations [4]. A Japanese study found that adding additional separation processes to collecting and presorting small e-waste could increase recovery rates for tantalum and gallium to 48% and 30%, respectively, and for gold from 26% to approximately 43% [147]. Hazardous metals are recycled infrequently and at low rates, mostly cadmium from nickel-cadmium batteries; however, collection rates still significantly impact overall recycling efficiency [148]. Only 10% to 20% of fluorescent light bulbs containing mercury are recycled worldwide [149]. 80% of all lead is used for backup power supplies and batteries in diesel and gasoline-powered cars [55]. Due to strict global regulations, collection and recycling rates for these uses are expected to reach between 90% and 95% [55]. As a result, lead used in batteries operates within an almost entirely closed-loop system.

5.7.2 Recovery of commodity materials: plastics

Studies suggest that commercially available technology can be used to generate net-zero emission plastics. Policies that encourage the adoption of circular carbon technologies must be developed and implemented to realise the potential. Two important technological advancements can be employed to attain net-zero emission plastics: (1) enhancing the plastic recycling rate and (2) implementing carbon capture. Economic incentives are necessary and one of the very important factors in achieving net-zero emission plastics and increasing the circularity of plastics. However, with the current setup, carbon emission pricing would only marginally encourage the circularity of plastic use. The exclusion of EoL management techniques, such as incineration, which falls under the purview of current emissions pricing schemes such as the EU emissions trading system, causes issues when transitioning from one life cycle stage to another. To increase recycling intensity, emission pricing schemes, including the incineration of plastic waste through policies such as extended producer responsibility, would play a vital role [150].

In terms of carbon pricing, the entire life cycle of plastics should be considered to enhance their circularity and fruitfully reduce GHG emissions. During policymaking, the increasing trend and availability of plastic waste should be addressed precisely. In addition, current regulations support the extraction of fossil fuels and oil, providing a cheap and plentiful substitute for CO₂, biomass, and plastic waste as renewable carbon feedstock. The vast infrastructural expenditures in the oil and gas sector have already paid off. In contrast, the use of CO₂, biomass, and plastic waste is still in its early stages, and the existing investment opportunities do not appeal to private investors due to the lower rate of return on investment. Consequently, potential investors are often discouraged from making the initial capital commitment, especially in the recycling sector [151].

Financial institutions, such as BlackRock, are increasingly considering climate impact in their investment decisions [152]. This shift could accelerate the path toward net-zero emission plastics by leveraging internationally approved policy tools, which enhance the availability of plastic waste as a resource and provide financial incentives for more significant investment in CO₂ utilisation and biomass applications. However, the potential reductions in energy use and GHG emissions must be carefully weighed against other environmental impacts of biomass and renewable electricity. For example, the use of biomass has been linked to increased water eutrophication and land acidification [153]. At the same time, the expansion of solar and wind power infrastructure has contributed to increased water consumption and metal depletion [154]. The circular carbon economy presents an opportunity to redesign future plastics production systems, eliminating reliance on fossil carbon resources. This approach could produce net-zero emission plastics with reduced operating costs and lower energy demands, striking a balance between environmental sustainability and economic feasibility.

5.8 Technological advancements in waste management

One of the most effective ways to mitigate the environmental impact of municipal waste is to adopt smarter, more technologically advanced methods in the waste processing industry. These state-of-the-art techniques help streamline collections, supervise waste disposal, and make it convenient for people and businesses to increase recycling rates and support the environment. Smart waste processing indicates systems that utilise technology to make waste processing more convenient and eco-friendly. Many uprising waste processing technologies use the Internet of Things (IoT) [142] (Figs. 5.9 and 5.10) to monitor waste collection more efficiently and make the process more sustainable. For example, smart waste bins [143] can monitor trash filling and pick-up to increase efficiency. Moreover, bio-based (using microbes) waste processing technology is also emerging as a sustainable processing alternative to deal with various wastes (Fig. 5.11).

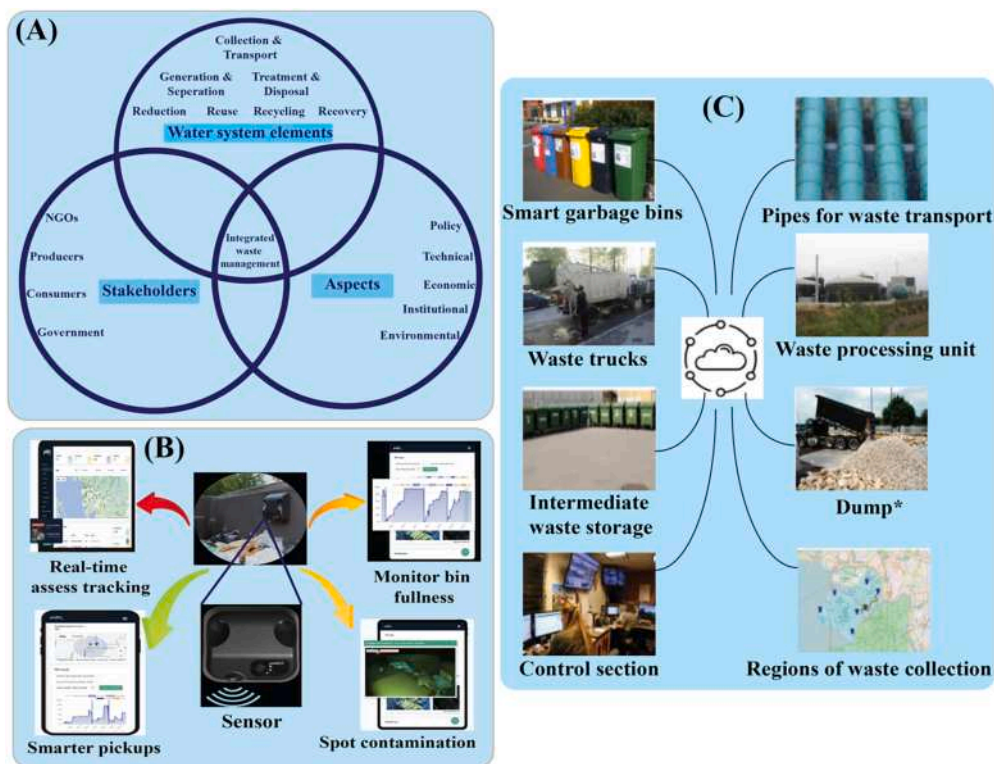


Figure 5.9 Integration of advanced technology in waste management: (A) Internet of Things based integrated sustainable waste management model [113], (B) functions of cutting-edge sensors by Pello, and (C) physical infrastructure of sustainable waste management systems [155].

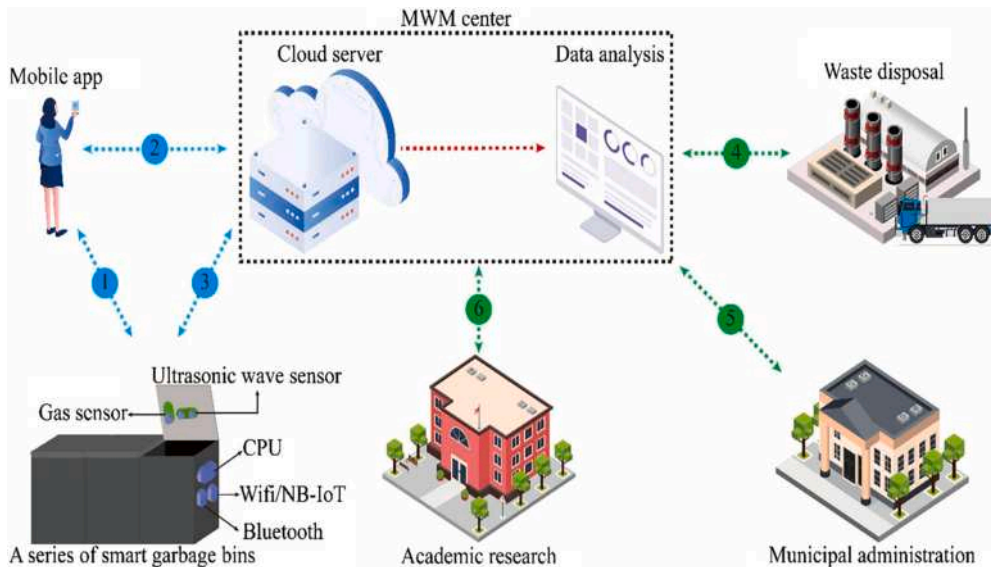


Figure 5.10 Deep-learning and Internet of Things (IoT)-based framework of municipal waste management (MWM) system [156].

5.8.1 Emerging technological advancement and future trends

Herein, some of the most recent and exciting emerging technologies are discussed. Among those emerging technologies is Pello, a technology developed for collecting waste more efficiently, thereby reducing environmental impact. Pello helps various companies worldwide achieve these goals in multiple ways. It provides instant updates on bin utilisation and reminders on a dashboard, assisting users in easily tracking bin capacity and preventing waste overflow, thereby minimising unnecessary clean-up expenses [158]. Access to this information helps you improve your waste management methods and ensure the proper disposal of your business's waste. It also ensures that garbage trucks are only dispatched when needed, which can help minimise gas emissions and alleviate traffic congestion. Artificial intelligence (AI) is an emerging technology that has the potential to significantly impact recycling. AI-powered robots can sort various materials from mixed waste [68]. Recycling industries are already utilising this technology to enhance the process's efficiency. Introducing AI robots in the recycling process helps efficient waste sorting and prevents recyclable materials from ending up in landfills. Besides, it allows waste processing companies to operate for a prolonged timespan or even stay open 24/7, significantly amplifying the volume of processed waste.

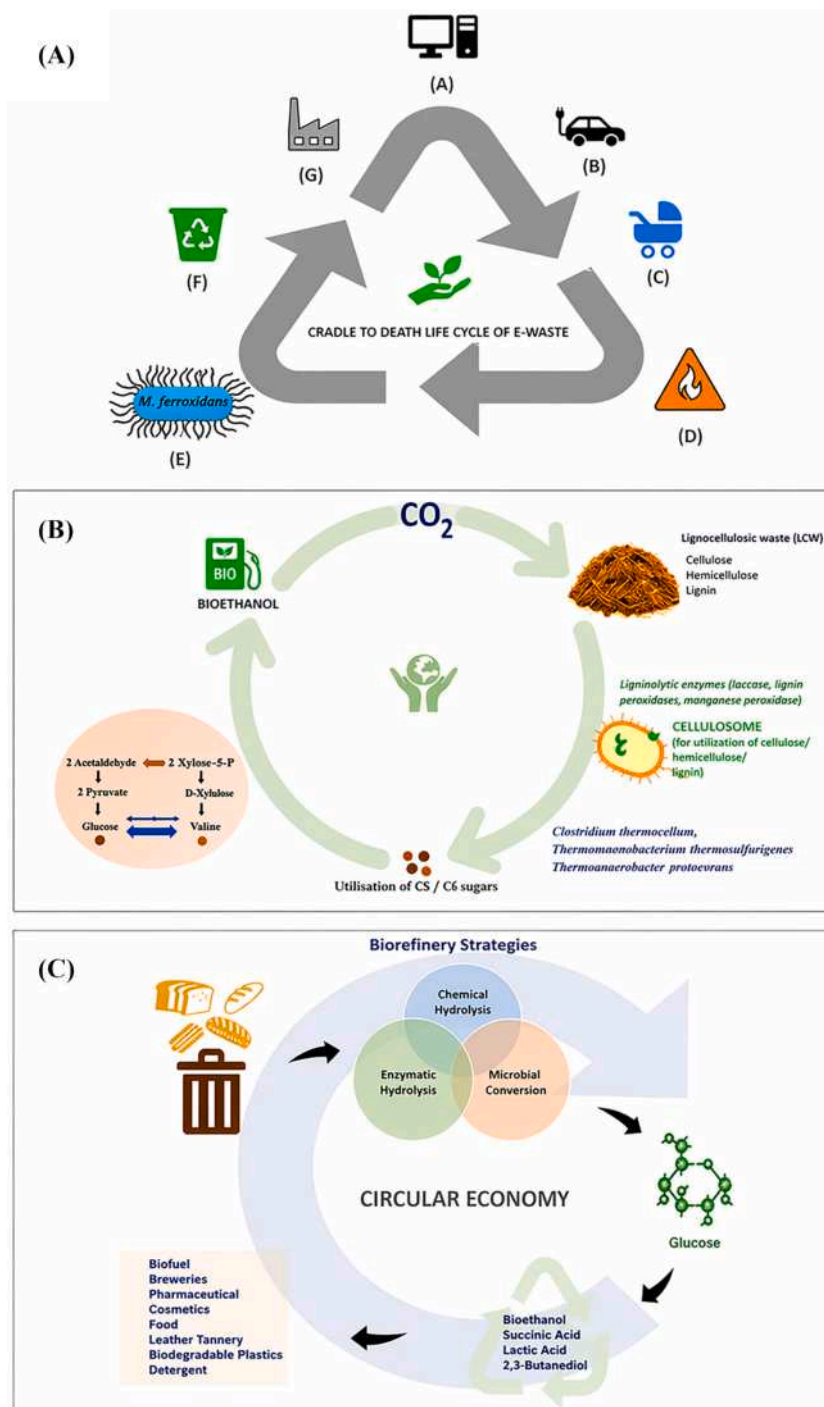


Figure 5.11 Modern bio-based waste management practices towards a circular economy: (A) cradle-to-grave life cycle assessment of e-waste, (B) fuel generation from lignocellulosic biomass by microbes and (C) bioprocessing of bread waste through various biorefinery strategies for production of value-added products using microbes [157].

As the community grows, traditional waste disposal and collection strategies become less practical. To counter this problem, one excellent solution is the utilisation of pneumatic pipes. Underground pipes could connect waste containers and processing units without requiring direct trash picking and transport [159]. Solar-powered trash compactors compress the garbage inside their dumpster to increase the storage capacity. This enables smart containers to accumulate up to fivefold more than conventional garbage bins [160]. The availability of the solar panel allows the trash compactor to be placed in locations without access to electricity, and the presence of a 12 V battery within the system makes it easier to put the trash compactor at local sites [160]. Besides the compressing facilities, the built-in waste level sensors of solar-powered trash compactors transfer data when the bin is full, allowing users to pick up the trash at the right time and streamlining the waste collection process.

A startup company introduced specialised e-waste recycling kiosks called ‘EcoATM’, enabling safe e-waste disposal [161]. For instance, used electronics (e.g. televisions, phones, smartwatches, tablets, computers) that are still functional can be traded in for cash, encouraging consumer participation and accelerating e-waste recycling. Mobile app technology also helps individuals and businesses navigate the recycling process. These apps enable users to donate food and clothes, locate a nearby recycling centre, and create a fantastic platform for environmentally conscious people who want to keep their waste out of landfills. With advanced features, some apps can provide information on which materials are recyclable. Apps that enable us to share unwanted items with others are excellent tools for fostering a sustainable and circular economy.

5.8.2 Challenges and opportunities

The practice of tech-driven waste management solutions is still in its preliminary stages [161]. Undoubtedly, it is an intricate issue that involves human behaviour, product designs, producers, and policymakers [162,163]. As such, it encompasses foundation and administration-related challenges in implementing the technologies. However, new-age solutions are comparatively new to other [164] established practices in waste processing—issues such as data security can compel constraints regarding the effectiveness of waste processing systems. At the same time, many researchers emphasise the need for waste processing to be approached through interdisciplinary studies, encompassing urbanism, social studies, engineering, ecology, economics, and ethics. Recent surveys only illustrate the technologies employed and their applications [162,165]. However, there is little negotiation and participation in policy-making from the governmental side, as well as in business models and executive decisions, which can accelerate or hinder the implementation of eco-friendly technologies. However, several obstacles are behind a smooth transition to the circular economy.

Therefore it is an innovative research platform investigating the barriers to implementing high-tech waste management solutions. In this context, the study should focus on the following two: (1) highlighting the key obstacles to high-tech waste management solutions in shifting to a circular economy and (2) to realise how these obstacles interact and how to bring all stakeholders to change effectively to sustainable high-tech waste management solutions in the transition to a circular economy. The research challenge is formidable due to its holistic nature, which demands innovative and state-of-the-art solutions and technologies. The issue is complex, encompassing a heterogeneous group of stakeholders that includes multiple government agencies, suppliers and buyers, technology suppliers, and waste processing entities. A timely solution requires a shift in behaviour, a profound reevaluation of current waste processing systems, and a transformation of the conventional linear economic model. The essential contributions should emphasise identifying the barriers to successful eco-efficient waste management. A comprehensive knowledge of these constraints can be acquired by analysing cause-and-effect dynamics. The outcomes should provide valuable insights for all stakeholders, including technology providers, end-users, governments, monitoring agencies, industry groups, and the public, to help overcome these challenges. The significant factors for improving waste management policy schemes should also be pointed out.

5.9 Social and behavioural aspects of waste management

5.9.1 Public awareness and education

In the waste management sector, it is said that waste management is 80% about people, and the remaining 20% is about technology. Everyone on this planet produces some form of waste and deals with managing it. Additionally, people accumulate waste, clear the streets by sweeping rubbish, and formulate decisions regarding waste management systems and community infrastructure. This summarises that people are the primary factor in changing the system. For this, initiatives such as campaigns, outreach programmes, and school- and community-based activities are necessary. The lack of expertise in waste management needs to be tackled globally. Speedy dissemination of knowledge, training programmes, and diploma courses are urgently required to develop a pipeline of skilled workers capable of addressing behavioural changes for the benefit of global health and environmental harmony. Countries with ample proficiency and steady leadership can create fast impacts regarding waste minimisation and processing.

5.9.2 Behavioural change strategies

Encouraging people to adopt waste management and reduction practices may feel challenging. However, the evidence around the globe reveals that when messages are profound, transparent, and reliable, people will embrace them and eventually change their behaviour. Examples from various countries show that social science can be implemented to inspire individual participation in waste management and reduction initiatives. Furthermore, it is also crucial to eliminate obstacles and make it convenient for individuals to engage by providing the correct infrastructure (e.g. sustainable food containers) and tailoring services to user needs (e.g. direct waste collection from households). In this case, incentives and motivational nudges can be helpful, for example, by increasing waste collection frequency or providing larger bins for waste disposal. Research and initiatives focused on correcting behaviour are more impactful when they consider and address how individuals experience and are affected by household waste. Knowledge alone is insufficient to change an individual's behaviours. People take decision-based experiences and sometimes look at other people's actions. They also react better to positive messages than negative ones; hence, encouraging the individual's behaviour is more efficient than focusing on the unwanted ones. Communities comprise various groups of people, each with distinct needs and priorities. Campaigns must take these disputes into account. For example, one campaign might incorporate different messages that local influencers convey through various platforms, such as public meetings, interviews, and social media.

5.9.3 Community involvement and stakeholder engagement

Community leaders deeply understand their people; therefore, leaders can try different strategies to minimise waste and encourage participation in waste management programmes (Fig. 5.12). Besides, allowing people to get involved and share their opinions can lead to new suggestions and help create a sense of responsibility and ownership within the community. Local governments and councils play a vital role in waste collection and management. As the custodians of waste generated by the community after collection, much of the regulation, policy enforcement, and legislative implementation depends on their willingness and understanding of waste mitigation challenges. Nongovernmental organisations (NGOs) can contribute significantly by actively participating in education and awareness campaigns. They play a crucial role in outreach activities, helping to educate community members and organisations on reducing the impact of waste. By doing so, NGOs support efforts to achieve a circular economy and meet net-zero targets [166].

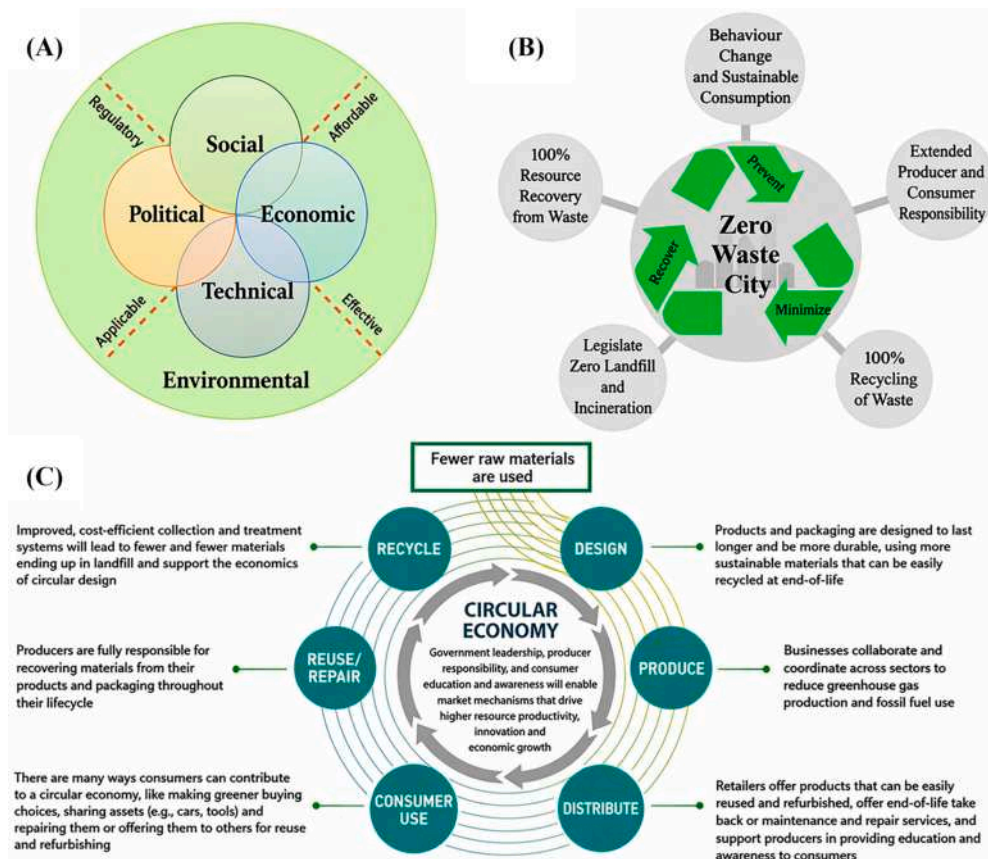


Figure 5.12 Summary of different components for zero waste city: (A) spheres in a zero waste city, (B) a holistic zero waste city model with key principles acting in parallel [166] and (C) Ontario's strategy for a waste-free Ontario.

5.10 Conclusion

Although promising examples of advanced recycling technologies exist, many remain in the demonstration phase. Greater emphasis must be placed on updating and modernising the current standard systems to achieve higher efficiency. Sorting and separation efficiencies are primarily determined by recycling technology, whereas collection efficiencies depend on governmental and societal factors. From a materials perspective, it is unfortunate that scale and cost limitations restrict the widespread use

of advanced technologies—such as laser, X-ray sorting, and NIR methods—instead, basic technologies such as shredding, magnetic sorting, and crushing dominate. Furthermore, product design often complicates dismantling and the release of materials, creating additional challenges. While bio-based materials are attractive due to their decomposition behaviour, their production still relies on plant-based resources. This reliance should be balanced by prioritising bio-waste resources over virgin materials. WtE initiatives show promise in generating renewable energy by utilising organic and plastic waste, effectively diverting it from landfills. The transition from a linear to a circular economy, aligned with net-zero goals, can create new green jobs. Achieving this transformation will require collective efforts from all stakeholders, including the government, policymakers, producers, and others, as well as significant shifts in consumer behaviour and consumption patterns. Sustainable product design, emphasising durable and recyclable materials, is essential. Transparency and standardisation at a global level must also be prioritised to drive meaningful progress.

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