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Project on Sustainable Plastic Waste Management

Draft report on approaches to plastic waste management in a carbon-neutral society

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Acronyms

BAU - Business-as-usual
BPA - Bisphenol A
CAPEX - Capital expenditure
DEHP - Di(2-ethylhexyl) phthalate
EIA - Environmental Investigation Agency
EMF - Ellen MacArthur Foundation
EOL - End-of-Life
EPR - Extended Producer Responsibility
EPS - Expanded polystyrene
ESM - Environmentally sound management
EU - European Union
GDP - Gross domestic product
GESAMP - Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG - Greenhouse gas
GIZ - German Agency for International Cooperation
HDPE - High-density polyethylene
HI - High-income economies
ICAO - International Civil Aviation Organization
IFC - International Finance Corporation
ILO - International Labour Organization
IMO - International Maritime Organization
INC - Intergovernmental Negotiation Committee
IRP - International Resource Panel
ISO - International Organization for Standardization
ISWA - International Solid Waste Association
IUCN - International Union for Conservation of Nature
LCA - Life Cycle Assessment
LDPE - Low-density Polyethylene
LiFE - Lifestyles for Environment
LLDPE - Linear low-density polyethylene
MMt – Million metric tonnes
NIVA - Norwegian Institute for Water Research
NPV - Net Present Value
OECD - Organisation for Economic Co-operation and Development
PCR - post-consumer recycled content
PE - Polyethylene
PET - Polyethylene terephthalate
PFASs - Polyfluoroalkyl substances
POPs - Persistent organic pollutants
PP - Polypropylene
PPA - Power purchase agreements
PS - Polystyrene
PVC - Polyvinyl chloride
R&D - Research and Development
RDF - Refuse-derived fuel
RPET - Recycled PET
SETAC - Society of Environmental Toxicology and Chemistry
SC scenario - Systems change scenario
SDG - Sustainable Development Goals
UNEP - United Nations Environment Programme
UNIDO - United Nations Industrial Development Organization
WEEE - Waste from Electrical and Electronic Equipment
WEF - World Economic Forum
WtE – Waste to Energy
WWF - World Wide Fund for Nature

Glossary

Additives - plastic is usually made from polymer mixed with a complex blend of chemicals known as additives. These additives, which include flame retardants, plasticizers, pigments, fillers and stabilisers, are used to improve the different properties of the plastic or to reduce its cost (The Pew Charitable Trusts and Systemiq 2020).

Business-as-usual (BAU) - see definition under ‘Scenarios’.

Bioplastic - plastic derived fully or partially from plant materials, such as cellulose, potato or corn starch, sugar cane, maize and soy, instead of petroleum or natural gas. Bio-based plastic can be engineered to be biodegradable or compostable. Still, they can be designed to be structurally identical to petroleum-based plastics, in which case they can last in the environment for the same period (UNEP Law and Environment Assistance Platform n.d.)

Biodegradable (materials) - a material that can, with the help of microorganisms, break down into natural components (e.g. water, carbon dioxide or biomass) under certain conditions (The Pew Charitable Trusts and Systemiq 2020).

CAPEX (capital expenditures) - funds used by an organisation to acquire or upgrade assets such as property, buildings, technology, or equipment.

Circular economy - one of the current sustainable economic models, in which products and materials are designed in such a way that they can be reused, remanufactured, recycled or recovered and thus maintained in the economy for as long as possible, along with the resources of which they are made, and the generation of waste, especially hazardous waste, is avoided or minimized, and greenhouse gas emissions are prevented or reduced, can contribute significantly to sustainable consumption and production (UNEP/EA.4/Res.1).

Circular plastic products - are designed to be reused safely many times, and their material is recycled or composted at the end of use, in practice and at scale, minimizing their adverse environmental impacts and respecting the rights, health and safety of all people involved across their life cycle (UNEP/PP/INC.1/7), including product users (adapted from UNEP/PP/ INC.1/7 to include health considerations).

Carbon budget - the total amount of carbon dioxide (CO_2) emissions that can be released into the atmosphere while still limiting global warming to a specific target, such as 1.5 or 2 degrees Celsius above pre-industrial levels. It sets a cap on the total greenhouse gas emissions that can be emitted over a certain period to stay within this target.

Closed-loop recycling - is the recycling of plastic into any new application that will eventually be found in municipal solid waste, essentially replacing virgin feedstock (i.e. plastic bottles, pen, etc.) (See ‘Recycling’) (The Pew Charitable Trusts and Systemiq 2020)

Compostable (materials) - materials, including compostable plastic and non-plastic materials, that are approved to meet local compostability standards (for example, industrial composting standard EN 13432, where industrial-equivalent composting is available) (The Pew Charitable Trusts and

Systemiq 2020)

Downcycling – recycling processes where the recovered material is of lower quality or functionality than the original material due to, e.g. structural strength, composition/impurities, colour or other properties.

Downstream activities — involve end-of-life management — including segregation, collection, sorting, recycling, and disposal. Recycling is a process that starts downstream and ‘closes the loop’ by connecting streams (i.e. starting a new life cycle for new plastic products with old materials). Similarly, repair/refurbishment processes provide another way to close the loop by bringing products back into the midstream (UNEP/PP/INC.1/7).

Dumpsites - places where collected waste has been deposited in a central location and where the waste is not controlled through daily, intermediate or final cover, thus leaving the top layer free to escape into the natural environment through wind and surface water (The Pew Charitable Trusts and Systemiq 2020).

End-of-life (EOL) – a generalised term to describe the part of the life cycle following the use phase.

Extended Producer Responsibility (EPR) – is an environmental policy approach in which a producer’s responsibility for a product is extended to the waste stage of that product’s life cycle. In practice, EPR involves producers taking responsibility for the management of products after they become waste, including collection, pre-treatment, e.g. sorting, dismantling, (preparation for) reuse, recovery (including recycling and energy recovery) or final disposal.

EPR systems can allow producers to exercise their responsibility by providing financial resources and taking over the operational aspects of the process from municipalities. They assume the responsibility voluntarily or mandatorily; EPR systems can be implemented individually or collectively (UNEP/PP/INC.1/6).

Feedstock – any bulk raw material that is the principal input for an industrial production process.

Geographic archetype - parts of the world with similar characteristics when it comes to plastic waste. The archetypes are divided into groups depending on country income, according to World Bank definitions: high-income economies, upper and lower-middle-income economies, and low-income economies. The rural and urban settings for each of the four income groups are also analysed separately to create eight geographic archetypes (The Pew Charitable Trusts and Systemiq 2020).

Incineration - destruction and transformation of material to energy by combustion.

Informal waste sector – where workers and economic units are involved in solid waste collection, recovery and recycling activities which are – in lor in practice – not covered or insufficiently covered by formal arrangements.

Leakage – materials that do not follow an intended pathway and ‘escape’ or are otherwise lost to the system. Litter is an example of system leakage (The Pew Charitable Trusts and Systemiq 2020).

Legacy (plastic) - plastics that cannot be reused or recycled, including plastics that are already in the environment as existing pollution or are stocked or will enter the economy, e.g. in short-lived or durable products designed without considering their circularity or long-term use in the economy.

Mechanical recycling - processing of plastic waste into secondary raw material or products without significantly changing the chemical structure of the material (ISO: 472:2013).

Microplastics – refers to particles less than five millimetres in diameter, including nano-sized particles (UNEP/EA.2/ Res.11).

Midstream activities — involve the design, manufacture, packaging, distribution, use (and reuse) and maintenance of plastic products and services. Keeping plastic products at midstream as long as possible is ideal for circularity, because this is where plastic products have their highest value (UNEP/PP/INC.1/7).

Mismanaged waste - collected waste that has been released or deposited in a place from where it can move into the natural environment (intentionally or otherwise). This includes dumpsites and unmanaged landfills. Uncollected waste is categorised as unmanaged (The Pew Charitable Trusts and Systemiq 2020).

Municipal Solid Waste (MSW) - includes all residential and commercial waste but excludes industrial waste.

Open burning - waste that is combusted without emissions cleaning.

Open-loop recycling - a process by which polymers are kept intact, but the degraded quality and material properties of the recycled material are used in applications that might otherwise not be using plastic (i.e. benches and asphalt) (The Pew Charitable Trusts and Systemiq 2020).

Plastic pollution - defined broadly as the adverse effects and emissions resulting from the production and consumption of plastic materials and products across their entire life cycle. This definition includes plastic waste that is mismanaged (e.g. open-burned and dumped in uncontrolled dumpsites) and leakage and accumulation of plastic objects and particles that can adversely affect humans and the living and non-living environment (UNEP/PP/INC.1/7).

Plastic Ubiquity: The pervasive presence of plastic materials and their derivatives (like microplastics) throughout the environment, both in natural and human-made settings.

Polymers:

- **PET** - Polyethylene terephthalate
- **HDPE -** High-density polyethylene
- **LDPE** - Low-density polyethylene
- **LLDPE** - Linear low-density polyethylene
- **PP** - Polypropylene
- **PVC** - Polyvinyl chloride
- **EPS** - Expanded polystyrene
- **PS** - Polystyrene

- **PA6** - Polyamide 6 (Nylon)

Recyclable - for something to be deemed recyclable, the system must be in place for it to be collected, sorted, reprocessed, and manufactured back into a new product or packaging—at scale and economically. Recyclable is used here as a shorthand for 'mechanically recyclable'. See 'mechanical recycling' definition (The Pew Charitable Trusts and Systemiq 2020).

Recycling – the processing of waste materials for the original purpose or other purposes, excluding energy recovery (ISO:472:2013).

Resin - a natural or synthetic solid or viscous organic polymer used as the basis of plastic, adhesives, varnishes or other products.

Reusable - products and packaging, including plastic bags, that are conceived and designed to accomplish within their life cycle a minimum number of uses for the same purpose for which they were adapted from the LEAP UNEP Plastic Glossary). In terms of 'minimum number of uses', the PR3 Standards suggest that reusable (containers) should be designed to withstand at least ten tenure cycles.

Reuse - means the use of a product more than once in its original form (ISO: 472:2013).

Reverse logistics - activities engaged to recapture the value of products, parts, and materials once they have reached end-of-use or end-of-life. All Value Retention Processes (such as reuse) may be part of a reverse logistics system. In addition, activities, including collection, transportation, and secondary markets, provide essential mechanisms for facilitating reverse logistics (IRP 2018).

Rigid plastics - see definition under 'Plastic categories'.

Rural vs. Urban - see definition under 'Urban vs. Rural'.

Safe disposal - ensuring that any waste that reaches its end-of-life is disposed of in a way that does not cause leakage of plastic waste or chemicals into the environment, does not pose hazardous risks to human health, and, in the case of landfills, is contained securely for the long-term (The Pew Charitable Trusts and Systemiq 2020).

Scenarios - for this report, we define the scenarios as:

> **Business as Usual (BAU):** Status quo of linear production and disposal, shaped by existing policies, markets, and consumer habits.
>
> **The Circular Plastics Revolution (CPR):** Idealized future of a fully circular plastic economy with net-zero emissions, assuming swift and comprehensive change.
>
> **Community-Driven Waste Management:** Approach prioritizing community-led waste solutions to supplement the limits of government programmes.

Hybrid Framework: Transitional phase strategically combining fossil fuel-based and bioplastics for a slow, gradual sustainability shift.

Single-use plastic products - often referred to as disposable plastics, are commonly used plastic items intended to be used only once before they are thrown away or recycled, e.g. grocery bags, food packaging, bottles, straws, containers, cups, cutlery, etc. (UNEP Plastic Glossary: https://leap.unep.org/knowledge/toolkits/plastic/glossary)

Systems change - captures the idea of addressing the causes rather than the symptoms of a societal issue by taking a holistic (or 'systemic') view. Systemic change is generally understood to require adjustments or transformations in policies, practices, power dynamics, social norms or mindsets. It often involves a diverse set of players and can take place on a local, national or global level (Ashoka Deutschland gGmbH and McKinsey & Company Inc. 2021); systems change requires modifications in many of the system structures, such as the mindset or the paradigm that creates the system or the system's goals or rules (Meadows 1999)

Upstream activities - include obtaining the raw materials from crude oil, natural gas or recycled and renewable feedstock (e.g. biomass) and polymerization. Plastic leakage into the environment (e.g. pellets and flakes) already happens at this stage (UNEP/PP/INC.1/7).

INTRODUCTION

Plastics are ubiquitous in modern society, permeating industries from food production and construction to healthcare and countless consumer goods. Their low cost, versatility, and durability have fuelled a surge in production, exceeding 460 million tons annually by 2019 (OECD, 2022). However, this unparalleled growth has precipitated a pervasive plastic pollution crisis with far-reaching consequences for ecosystems and human health. Furthermore, the greenhouse gas emissions generated throughout the plastic lifecycle, particularly carbon dioxide, pose a significant threat to global climate goals.

The growing awareness of the environmental challenges posed by plastics has led to a surge in research aimed at finding solutions. This body of work sheds light on the significant carbon footprint associated with plastics, their reliance on fossil fuels, the shortcomings of current recycling infrastructures, and the severe consequences of mismanaging plastic waste, including its harmful effects on ecosystems and human health. Despite the availability of mitigation strategies, transitioning to a sustainable plastics economy necessitates a comprehensive, multidisciplinary approach. Such an approach encompasses the entire lifecycle of plastics, addresses their carbon footprint, and integrates economic consideration legal frameworks to ensure a holistic and effective transition.

The growing international focus on this issue is evident in recent initiatives by the World Trade Organization, World Bank, OECD, and other international institutions. A landmark event occurred in March 2022 at the UN Environment Assembly (UNEA-5.2) with the adoption of a historic resolution to develop a legally binding international instrument on plastic pollution. This treaty has the potential to mandate sustainable production and consumption practices, harmonize fragmented regulations, and enhance legal certainty.

This report examines the current state of the plastics economy and proposes a shift towards a circular, low-carbon model. It evaluates this transition against various scenarios, including business-as-usual, an intermediate hybrid model, and a community-driven approach. The report outlines feasible pathways to achieve this transformation, anchored by four interrelated objectives: reducing plastic consumption, transitioning to renewable feedstocks, improving recycling processes, and minimizing the carbon footprint along with other environmental impacts. These goals are designed to work in concert to eliminate environmental burdens and foster a sustainable plastics economy. To realize these ambitious targets by 2050, we must take immediate action, adopt innovative design principles and support comprehensive systemic change.

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1. Chapter One: Current State of Plastic Waste

This chapter offers a broad overview of plastics, addressing critical issues such as the reliance on fossil fuels for plastic production, the increasing trends in plastic waste generation, and the regional variances in plastics production and consumption. It delves into the quantitative aspects of plastic waste and explores the complex feedback loops that plastic pollution creates within environmental systems. By interlacing these topics, the narrative tries to bring a holistic view of the challenges and impacts that arise throughout the lifecycle of plastics, tracing their journey from fossil fuel-based origins to their widespread distribution across the planet.

1.1 Plastic waste in numbers

Plastic waste can be categorized according to its source, type, recycling potential and pollution concern (Geyer, 2020). Sources encompass, among other things, post-consumer waste, industrial waste and commercial waste. Plastic types include PET, HDPE, PVC, LDPE, PP, and PS. Plastics are classified as recyclable or non-recyclable based on their reusability. Pollution concerns revolve around microplastics and single-use plastics. A comprehensive understanding of these categories is essential for the development of effective waste management and recycling strategies. Plastic packaging and small non-packaging plastic items (PPSI) constitute the most widespread use of newly produced plastics and make up the most significant portion of post-consumer plastic waste (Winterstetter et al., 2023).

In 2019, around 65% of the global mismanaged plastic waste took place in Asia, highlighting a significant challenge in waste management. In Latin America and the Caribbean, approximately 19% of plastic waste is mismanaged, and the region collectively produced 231 million tonnes of waste in 2016, with a notable portion (52%) consisting of food and green waste. Despite their minimal contribution of 1.64% to global plastic waste generation and 1.56% to mismanaged plastic waste, Small Island Developing States (SIDS) face a significant burden from plastic litter washing up on their shores from offshore sources, leading to a disproportionate impact on these small islands. The management of plastic waste in Europe and the Balkans shows varying levels of effectiveness, with national shares of mismanaged plastic packaging waste in Europe ranging from 2% to 49%. These studies underscore the need for targeted interventions and improved waste management strategies across different regions to address the global plastic waste crisis effectively (Brooks et al., 2020).

Plastic waste mismanagement has emerged as a significant environmental concern, with several studies highlighting its extent. Three prominent works of the last decade provide distinct perspectives and methodologies on the issue, highlighting the complexity of accurately quantifying waste (Borrelle et al., 2020; Jambeck et al., 2015; Lebreton & Andrady, 2019; Meijer et al., 2021). Jambeck et al. focused on coastal regions, estimating plastic inputs into the ocean at 4.8-12.7 million metric tonnes (mt) annually in 2010. Expanding the scope, Borrelle et al. estimated plastic leakage into all aquatic ecosystems at 19-23 million mt in 2016, representing 11% of global plastic production. Notably, Lebreton and Andrady adopted a high-resolution approach (~1 km) to estimate plastic generation and mismanagement globally, offering insights into localized hotspots.

In contrast, Meijer et al.'s study on riverine plastic leakage revealed that more than 1,000 rivers contribute to 80% of global annual plastic emissions, with quantities ranging between 0.8 and 2.7 million metric tons. The research highlights small urban rivers as disproportionately significant sources of this pollution, indicating that plastic emissions are more widely dispersed across numerous rivers than previously estimated—by up to two orders of magnitude. This insight shifts the understanding of plastic distribution and emphasizes the need for widespread mitigation efforts.

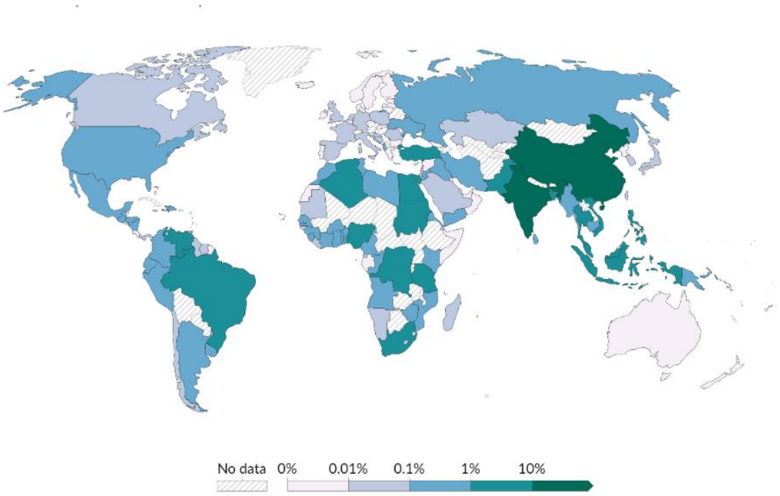

Figure 1-1: Plastic waste emitted to the ocean per capita, 2019.
Source: Meijer et al., 2021

Figure 1-2 compares the management and disposal of plastic waste across different global regions. From the chart, mismanaged plastic waste varies significantly by region, with Sub-Saharan Africa having the highest proportion at 64% and the United States has the lowest at 4%. Recycling rates also vary, with the highest in Europe at 38% and the lowest in Oceania and Sub-Saharan Africa at 7% and 6%, respectively. The chart provides a visual representation of the disparities in plastic waste management across the globe, highlighting the need to tailor waste management practices to specific regions, particularly where mismanaged waste is most prevalent.

Studies involving the classification of plastic waste into distinct management routes, termed end-of-life fates, employ variable end-of-life shares based on country, polymer type, and waste classification (OECD, 2022). This treatment encompasses Municipal Solid Waste (MSW) and other plastic waste types, which are subject to recycling, incineration, or disposal operations. Disposal is further subdivided into sanitary landfilling, mismanaged waste, and, for MSW, litter—a separate category acknowledging its unique origins and prevalence in areas lacking essential waste management infrastructure. The OECD 2022 report thoroughly examines the landscape of plastics production, utilization, and waste generation, elucidating the economic forces underpinning these activities while charting the associated environmental consequences on a worldwide scale. Using 2019 statistics as a baseline, the determination of end-of-life fate percentages varied regionally. Recycling rates for plastics, defined as materials collected for this purpose, derive from a variety of sources, primarily national data. Rectifying potential underestimations from informal recycling or inflated official figures requires a thorough review process was applied, incorporating expert feedback and analytical modelling by Ed Cook, Josh Cottom, and Costas Velis of the University of Leeds. The distribution of recycling percentages among polymers adjusts overall rates by factors reflecting each polymer's recyclability and market value. These factors, determined through expert consultation, ensure calculated recycling volumes remain within actual capacity limits, taking into account data constraints.

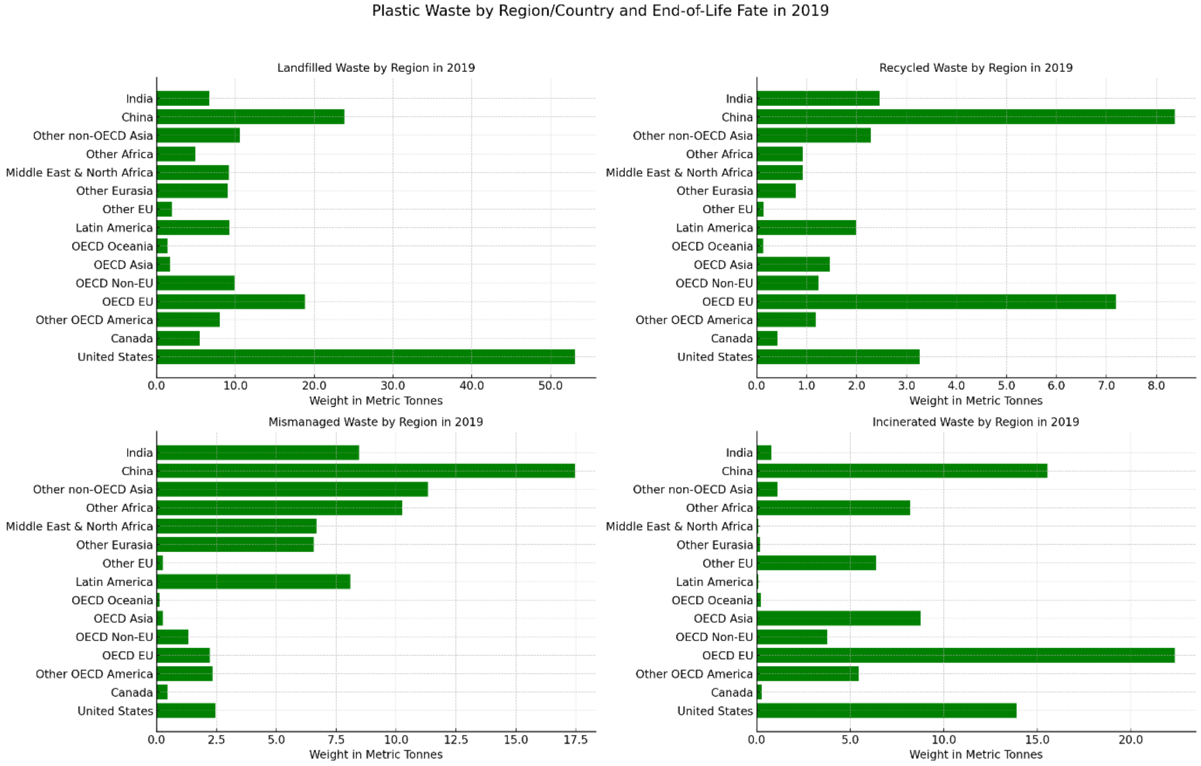

Figure 1-2: End of Life fate of plastic waste across the world
Source: (OECD, 2022)

1.2 Trends in Plastic Waste Generation

Historical data depicts a steep increase in plastic production and waste generation over the past five decades (OECD, 2022). According to the OECD report, between the 1970s and 1990s, plastic waste generation tripled, mirroring a similar rise in production. Notably, the early 2000s witnessed a more significant increase in plastic waste than the preceding four decades combined. Currently, annual plastic waste generation stands at an estimated 400 million tonnes. Further analysis reveals that since the 1970s, the growth rate of plastic production has surpassed that of any other material.

According to OECD (2022), global plastic waste generation is projected to significantly increase from 2020 to 2060, with the amount of plastic waste generated worldwide expected to triple, surpassing one billion metric tons by Various factors, such as the use of plastics in packaging, construction, and other applications drive this exponential growth. Plastic use is projected to triple between 2019 and 2060, from 460 million tonnes to 1,321 million tonnes, mainly due to economic growth and rising incomes globally. The share of recycling as a waste management practice is expected to rise to 17% in 2060, up from 9%

in 2019. Despite efforts to increase recycling and reduce mismanaged plastic waste, the environmental consequences of this significant increase in plastic waste generation remain a pressing global issue.

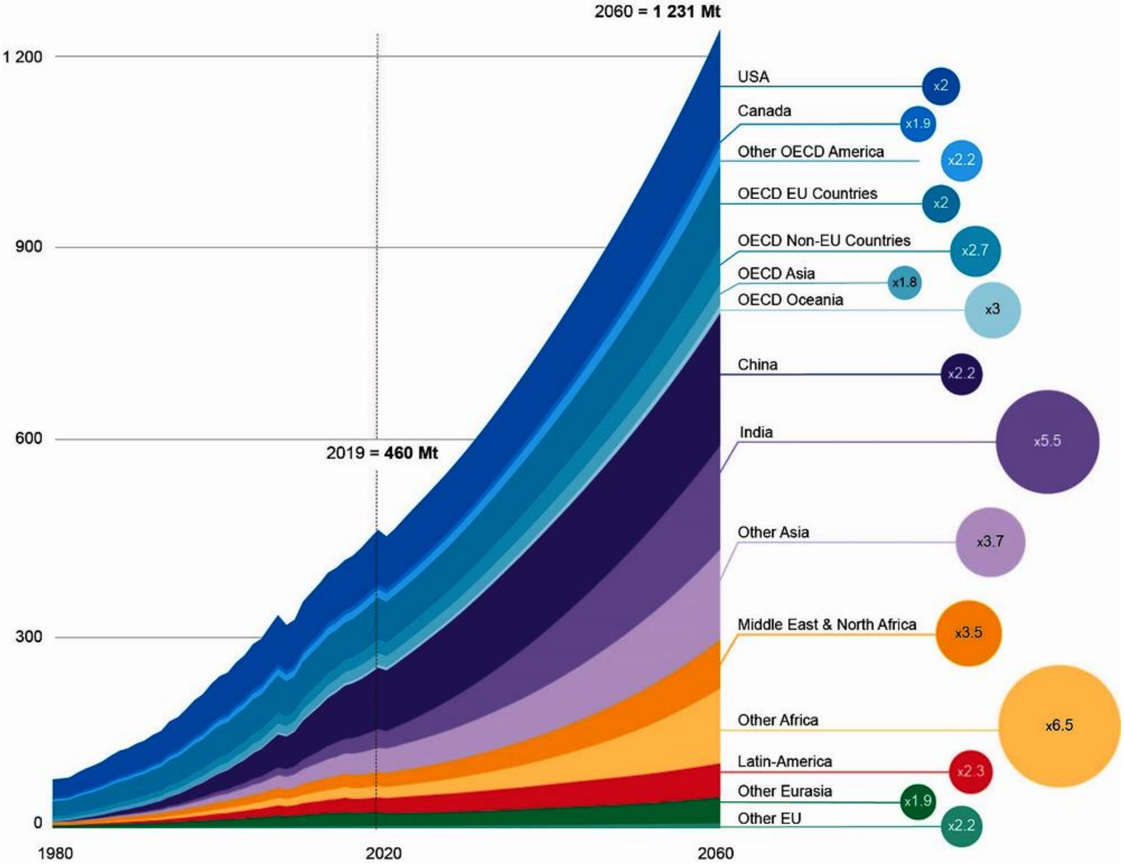

Figure 1-3: Projected total global plastic waste generation by region in 2060
Source: (OECD, 2022)

1.3 Plastic pollution feedback loops

Exposure to plastic is expanding into new environmental areas and the food chain as plastic products break down into smaller particles, concentrating toxic chemicals. With the increasing production of plastic, this exposure is expected to escalate (Dimassi et al., 2022). Research on the impacts of plastic is shedding light on the complex and significant health effects that occur throughout its lifecycle, from production to disposal (Nayanathara et al., 2024). These effects manifest in various forms of pollution, including air, water, and soil contamination. The global threat that plastic poses to human health is driving a worldwide push for reducing plastic production, use, and disposal. To effectively address these challenges, it is crucial to develop a comprehensive understanding of the broader impacts of chemicals and plastics on both the environment and human health across the entire plastic lifecycle. Table 1 provides a non-exhaustive summary of how plastics and their chemical additives can impact the environment and human health throughout the plastic lifecycle. It includes linkages and potential co-benefits with other environmental objectives like climate and biodiversity, which are vital to consider when developing future strategies for a sustainable plastics economy.

Life cycle phase	Environment	Human health
Sourcing/ extraction phase	- Heavy reliance on fossil fuels, including hydraulic fracking, for extraction of hydrocarbons and associated pollution	- Harmful chemicals used in oil and gas extraction, including fracking, can enter drinking water resources from spills and improper handling of wastewater.
Chemical phase	- High energy intensity of the petrochemical industry and its processes - Emissions and releases of pollutants to surface and groundwater negatively affect ecosystems	- Transforming fossil fuels into polymers and chemicals used in plastics may release carcinogenic and other highly toxic chemicals that may cause occupational exposure and may pollute neighbouring communities
Material phase (Manufacturing)	- Production and transportation of plastic pellets, powders and flakes is a source of microplastic releases due to spills and poor handling procedures.	- The production of materials and products releases toxic chemicals into the air, jeopardizing the health of workers.
Material phase: (consumption)	- Consumption of unnecessary and problematic products (including microplastics in products) leads to excessive waste generation and contributes to littering that affects marine, freshwater and terrestrial ecosystems. - Toxic chemicals and microplastics may be released from products during their intended use, resulting in environmental exposure.	- Toxic chemicals may be released from products during their intended use, resulting in human exposure.
End of Life phase (Plastic waste)	- Leakage of plastics and associated chemicals of concern to the environment due to improper disposal at the end of life (open dumps, burning), inadequate wastewater treatment (including the application of sewage sludge as fertiliser on agricultural fields), and dumping and discharges from shipping - If incinerated at end-of-life, plastics will emit embodied carbon as CO2 and may also release pollutants (e.g., UPOPs). If landfilled, there is a risk of landfill fires and slow degradation with associated methane emissions, as well as toxic chemicals.	- Chemicals present in plastics may impair recycling processes and the safety and quality of recycled materials. - Waste management in improper conditions releases highly toxic chemicals into the air, water and soil, which may lead to human exposure, including within neighbouring communities.

Table 1. Environmental and human health concerns across the life cycle of plastics

Sources: (Azoulay et al., 2019; Karasik et al., 2023; Shams et al., 2021)

1.3.1 Ocean warming

Ocean warming, driven by greenhouse gases like carbon dioxide, is causing significant changes in marine ecosystems, sea levels, and global weather patterns (Hoyme et al., 2022). The ocean absorbs 90% of excess energy generated by human activities since 1971, leading to a 1.5°F warming in the top 700 meters since 1901. This warming alters marine biodiversity, ocean chemistry, and sea levels and influences extreme weather events. Factors like heat distribution, ice melting, and ocean circulation changes influence variations in warming. Ocean warming intensifies storms like hurricanes and poses threats to marine ecosystems, fisheries, and coastal communities world (Hoyme et al., 2022).

Plastic leakage into the environment contributes to ocean warming through various mechanisms. Plastics are derived from fossil fuels and emit greenhouse gases throughout their lifecycle, from production to disposal, with a significant impact on climate change. Plastics in the aquatic environment contribute directly to methane and ethylene emissions when exposed to UV, further exacerbating the greenhouse effect. The flow of plastics leaking into aquatic environments is projected to increase significantly by 2060, posing a severe challenge to marine biodiversity and ecosystems (Sharma et al., 2023).

1.3.2 Toxic pollutants from the open burning of plastic waste

The combustion of plastic waste significantly contributes to atmospheric pollution. Frequently, municipal solid waste, up to approximately 12% to 18% plastic, is incinerated, emitting noxious gases, including dioxins, furans, mercury, and polychlorinated biphenyls (US EPA, 2023). Additionally, burning polyvinyl chloride releases hazardous halogens, exacerbating air pollution and contributing to climate change. The resultant dissemination of toxic substances poses considerable risks to vegetation, human and animal health, and the broader ecological system. Specifically, polystyrene exposure harms the central nervous system, while brominated compounds exhibit carcinogenic and mutagenic properties. Dioxins, notably persistent organic pollutants (POPs), accumulate in crops and water systems, infiltrating the human diet and bodily systems. The most harmful Dioxin variant, 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), commonly known as Agent Orange, is linked to cancer, neurological impairment, and disruptions in reproductive, thyroid, and respiratory functions. Consequently, the incineration of plastic waste heightens the risk of cardiovascular diseases, exacerbates respiratory conditions such as asthma and emphysema, and can cause dermatological, gastrointestinal, and neurological disorders (Pathak et al., 2024).

1.3.3 GHG Emissions due to incineration

In the context of municipal waste incineration, the emission of fossil CO2 varies significantly based on the composition of the waste being incinerated. Given the substantial presence of plastics, which originate from fossil sources, within the waste stream, it is estimated that approximately 580 grams of CO2 are emitted for every tonne of waste combusted (Environment Agency, 2020). This estimation underscores the environmental impact of incinerating waste materials that contain fossil-derived components and is particularly significant according to the European Strategy for Plastics in a Circular Economy, which posits that the production and incineration of plastic waste contribute to an estimated 400 million tonnes of CO_2 emissions globally each year(Awasthi et al., 2019).

The incineration of plastics holds a crucial position within the larger framework of climate change and environmental impact. Municipal waste statistics further underscore the extent of waste incineration and its contribution to CO2 emissions. The 'Pollution Inventory Reporting – Incineration Activities Guidance Note' offers valuable insights into the regulatory and environmental dimensions of waste incineration, emphasizing the necessity for meticulous management and oversight of this process (Yap et al., 2015)

1.3.4 Impact of plastics on wildlife

Plastic pollution poses a critical threat to wildlife throughout the planet. Both land and aquatic ecosystems suffer as animals encounter this omnipresent waste. One significant danger is entanglement, primarily in discarded fishing gear and plastic debris. These entanglements cause crippling injuries to species ranging from tiny fish to majestic whales, hindering their movement, feeding, and ability to escape predators – often leading to fatal consequences like drowning, strangulation, or starvation. Additionally, animals weaken and become more susceptible to disease and predation due to the prolonged suffering and limitations caused by entanglement (Kumar et al., 2021).

The ingestion of plastic, particularly microplastics, intensifies the problem for marine and terrestrial animals (Ramon-Gomez et al., 2024), as mistaking these particles for food leads to internal blockages, resulting in malnutrition and starvation. The plastics also release harmful toxins that accumulate in their bodies, causing long-term health issues or immediate death. Plastic pollution is particularly detrimental for smaller organisms like plankton, whose reduced reproduction and increased mortality disrupt the base of the marine food web. Plastic pollution extends its negative impact beyond individual animals, affecting entire ecosystems. It disrupts biodiversity by transporting invasive species and physically damages crucial habitats like coral reefs.

1.3.5 Effect of plastics on soil fertility and land degradation

The mismanagement of plastic waste has led to significant environmental challenges, including the proliferation of plastic fragments in oceans and soils, as highlighted in a recent systematic literature review. In agricultural contexts, practices such as plastic mulching contribute to the accumulation of plastic residues in the soil. These residues undergo fragmentation into microplastics (MPs) through physical, chemical, and biological processes, including ultraviolet radiation and erosion. MPs, defined as particles smaller than 5 mm, pose a global environmental concern, particularly impacting soil health, a topic that has garnered less attention compared to other environmental impacts. The primary sources of MPs in soil environments include agricultural activities, sewage sludge application, and tyre wear, with significant quantities entering North American and European soils annually through these channels. The transformation of plastics into MPs, and subsequently into nanoparticles due to photo-oxidative degradation, further exacerbates their environmental footprint(Sajjad et al., 2022).

Recent studies report the presence of microplastics and nanoplastics[1] across various ecosystems and their adverse effects on soil systems and agricultural productivity. Integrating MPs into soil disrupts its

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[1] Microplastics are plastic particles with a diameter smaller than 0.5 millimetres, comparable to the size of a grain of rice. Nanoplastics, which are significantly smaller, have diameters of 100 nanometres or less. To contextualise, one nanometre equals one-millionth of a millimeter. Given that the diameter of an average human hair ranges between 80,000 and 100,000 nanometres, nanoplastics are approximately 800 to 1,000 times smaller than a human hair strand, underscoring their minuscule dimensions.

structure, alters physicochemical properties, and impacts nutrient dynamics, affecting crop development, germination rates, and overall plant health. The implications of MPs extend to transforming soil aggregation, moisture retention, microbial activity, and even influencing greenhouse gas emissions. These findings indicate a pressing need for comprehensive understanding and mitigation strategies to address the ecological risks associated with MPs, especially given their potential to compromise food security ((Junhao et al., 2021; Kumar et al., 2021).

Plastic waste disposal in landfills poses a significant environmental threat, as hazardous chemicals from additives like plasticizers and flame retardants leach into soil and water, contaminating ecosystems and drinking sources (Maddela et al., 2023). Environmental conditions and the natural degradation of plastics intensify the leaching of harmful compounds such as bisphenol A (BPA) and phthalates into the environment. These substances can accumulate in the tissues of living organisms, leading to bioaccumulation and biomagnification through the food chain, exposing higher trophic levels to toxic levels of these chemicals. Furthermore, the soil's composition and fertility are compromised, impacting plant growth and disrupting the ecological balance by harming essential microorganisms. This situation highlights the urgent need for improved waste management and reduced plastic usage to protect environmental and public health and ensure ecosystem sustainability.

Selected best practices in plastic waste management across the globe.

1. Enhanced Solid Waste Management Systems: The Maldives, renowned for its pristine ecosystems, has embarked on a comprehensive overhaul of its waste management infrastructure to mitigate the adverse impacts of escalating waste and litter. The country's efforts focus on developing sustainable disposal methods, optimizing waste collection, and zoning islands for efficient resource utilization. These measures aim to tackle plastic waste at its source, ensuring the longevity of its natural habitats (Wang et al., 2024).

2. Leveraging composting to reduce emissions: A $5.5 million project in Pakistan supported the development and expansion of a composting facility in Lahore. This project facilitated market development for the facility and enabled it to participate in the emissions reduction credit program under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). As a result, the project achieved a reduction of 150,000 tonnes of carbon dioxide equivalent (CO2e) and significantly increased the daily compost production volume from 300 tonnes to 1,000 tonnes. (Iqbal et al., 2023).

3. Policy and Strategic Planning: Implementing focused interventions, like California's ban on specific types of plastics, which led to a 72% reduction in plastic litter on beaches between 2010 and 2017, illustrates the importance of targeted policies. However, the effectiveness of such bans depends on the underlying waste management infrastructure and the government's enforcement capabilities. Without adequate collection, disposal systems, and incentives for compliance, efforts to ban plastics may face challenges such as noncompliance and the emergence of "black markets" for banned materials.

2. Chapter Two: Plastic Pollution and Climate Change

2.1 Carbon emissions across the lifecycle of plastics

In 2019, the ground breaking report titled "Plastic and Climate" highlighted the impact of plastic on greenhouse gas emissions (Lisa Anne & Steven, 2019). The study revealed that in the same year, GHG emissions due to plastics were equivalent to 850 million tonnes of carbon dioxide (CO2). These emissions arise from various stages of the plastic lifecycle, including production, transportation, and incineration. Additionally, the report emphasized the detrimental effects of plastic on phytoplankton, which contribute to the ocean's carbon sequestration process. The findings of this comprehensive report underscore the urgent need for global action to curb plastic pollution and mitigate its devastating impact on the climate and marine ecosystems.

Plastic production begins with the extraction and distillation of plastic resins (Gardiner, 2019). These resins are then converted into various products and transported to the market. Each step of this process, directly or through its energy requirements, contributes to greenhouse gas emissions. Significantly, the carbon footprint of plastics extends beyond their active use phase, encompassing end-of-life management practices such as landfilling, incineration, recycling, and composting (relevant to specific plastics).

Furthermore, the incineration of plastic waste in waste-to-energy facilities often produces higher carbon dioxide emissions than traditional fossil fuel combustion. This reality poses a direct challenge to achieving carbon neutrality, emphasizing the need for a strategy shift in the production and disposal of plastics. Another obstacle is landfill methane emissions resulting from the disposal of plastic waste in landfills. As plastic waste undergoes anaerobic degradation in landfills, it emits methane, a GHG with a global warming potential 25 times greater than carbon dioxide over 100 years. Hence, reducing plastic waste in landfills is a matter of waste management and a critical step towards carbon neutrality (Wang et al., 2024).

Stage	2015	2019	Absolute Change	Relative Change
All lifecycle stages	1,664 MMT	1,788 MMT	+123 MMT	7%
Production and conversion	1,502 MMT	1,595 MMT	+92 MMT	6%
End-of-life	162MMT t	193 MMT	+31 MMT	19%

Table 2. Aggregate GHG Emissions across the Lifecycle of Plastics
Source: Saunios et al., 2019

Analysing the complete life cycle of fossil fuel-based plastics reveals that a significant proportion - approximately two-thirds- of their greenhouse gas emissions occur during the initial stages of extraction and production (Bauer et al., 2022). The conversion of plastic into products like pipes, bottles, and bags contributes less than a third of plastic-related emissions. The remaining emissions stem largely from disposal, emphasising the potential for plastic recycling to significantly lessen the environmental impact of plastic by reducing the need for extraction and resin production, which are emission-heavy processes (Geyer, 2020).

As we can see, each treatment method contributes to releasing carbon dioxide, either directly or through energy or consumables (evident, for instance, in the case of landfill disposal). Consequently, the entire life cycle of plastics translates to a 3.8% contribution to global greenhouse gas emissions. Table 2 displays the total greenhouse gas (GHG) emissions from plastics across their lifecycle from 2015 to 2019, categorized into three stages: overall lifecycle, end-of-life, and production and conversion. During this period, GHG emissions from plastics saw a 7% increase, with the end-of-life stage experiencing the highest growth (19%). Specifically, emissions across all lifecycle stages rose by 123 million metric tonnes (MMT), marking a 7% growth. The end-of-life emissions surged by 31 MMT (19%), and production and conversion emissions grew by 92 MMT (6%). These numbers highlight the end-of-life stage, which showed the most significant increase.

2.1.1 Extraction and Transport

Fossil fuel extraction and transportation are significant sources of greenhouse gas (GHG) emissions (Shen, 2020). Natural gas extraction, processing, and storage generate direct and indirect emissions. Direct emissions come from methane leaks and fossil fuel-powered vehicles and drilling machinery. Indirect emissions stem from the energy needed to power these processes. The emissions involve land use changes for infrastructure development, leading to deforestation and loss of carbon sinks, thereby elevating atmospheric CO_2. Research highlights the environmental impact of these processes, with emissions from oil extraction and refining central to plastic production reaching roughly 108 million metric tons of CO_2e annually (Lebreton & Andrady, 2019).

2.1.2 Production

Plastic manufacturing is one of the most significant contributors to greenhouse gas emissions within the manufacturing sector, marking it as rapidly expanding and environmentally detrimental. Manufacturing plastic involves a sequence of energy and emissions-intensive steps, including cracking alkanes into olefins, polymerising and plasticising these olefins into plastic resins, and various other chemical refining operations. This complex process is energy-demanding and significantly contributes to the sector's carbon footprint. As a parameter, in 2015, 24 ethylene production facilities in North America were responsible for emitting 17.5 million metric tons of CO_2 e (Azoulay, 2019). Conventional cracking, a process used in the production of ethylene, emits roughly 1.5 metric tonnes of carbon dioxide for every metric tonne of ethylene produced. Globally, this equates to over 260 million metric tonnes of CO_2 emissions each year. These emissions constitute nearly 0.8% of the world's total carbon emissions, which the Global Carbon Project estimated to be 34 billion metric tons in 2020, highlighting the contribution of this process to climate change.(Mann, 2021; Tenhunen-Lunkka et al., 2023). The construction of new ethylene facilities underscores the upward trajectory of plastic-related emissions.

These projects are part of a broader trend, with near 1,500 new and expanded petrochemical projects expected to start operations in the world during 2023-2027 period.*

2.1.3 Disposal

In 2019, plastics accounted for 1.8 billion tonnes of GHG emissions, representing 3.4% of global emissions, with 90% originating from production and conversion from fossil fuels. Projections indicate that by 2060, emissions from the plastics lifecycle will surpass 4.3 billion tonnes of GHG emissions, more than doubling the current levels. At the end of their life cycle, plastic accounts for about 10% of their total greenhouse gas (GHG) emissions, with the disposal method significantly affecting these figures (OECD, 2022). Incineration is the primary source, generating over 70% of these emissions in 2019, with similar projections for 2060, followed by the emissions from recycling processes. However, recycling is essential for reducing GHG emissions by creating secondary plastics that replace new, primary plastics, thus decreasing the need for fresh plastic production. The impact of recycling on GHG emissions varies depending on the type of plastic and the region, mainly because of the different energy sources used in recycling operations across various areas. On average, recycling reduces emissions by at least 1.8 tonnes of CO_2 equivalent for each recycled polymer tonne, representing a reduction of more than two-thirds of the GHG emissions compared to the production of new plastics (OECD, 2022). The analysis does not cover GHG emissions from plastics that leak into the environment. Nonetheless, recent studies (like Shen et al., 2020, which builds on Royer et al., 2018 experiments) show that the degradation of plastics in nature and unsanitary landfills can lead to methane emissions, estimated at around 2 million tonnes of CO_2 equivalent annually.

2.2 Impact of Plastics on global carbon budgets

Analysing data from sources like the IPCC and Material Economics to understand the impact of plastic production on global carbon budgets (Economics, 2019; Lee et al., 2023). The IPCC AR5 sets a limit of 800 Gt for cumulative industrial sector emissions by the end of the century, with Material Economics allocating 300 Gt CO_2e to this sector (IPCC, 2022). The rapid growth in plastic production is a significant contributor, with projections suggesting an increase from 380 million metric tons in 2015 to 1,323 million metric tons by 2050, potentially leading to annual emissions of up to 2.5 Gt (Economics, 2019). According to Global life-cycle greenhouse gas (GHG) emissions from conventional plastics were 1.7 gigatons of CO2-equivalent (CO2e) in 2015 and are expected to rise to 6.5 gigatons of CO2e by 2050 if current trends persist (Zheng et al., 2019).

If developing countries adopt industrialization patterns observed elsewhere, emissions could reach 350 GtCO_2 by 2050, constituting a significant portion of the remaining budget needed for a 50% chance of staying within IPCC limits (Trout et al., 2022). Plastic GHG emissions are projected to account for 15% of the global carbon budget by 2050 if current trends continue. Despite these projections, a comprehensive evaluation of global strategies to mitigate the life cycle GHG emissions of plastics is lacking. Zheng et al. based their conclusions on a dataset covering ten conventional and five bio-based plastics to assess their life cycle GHG emissions under various mitigation strategies.

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* Research and Markets (2023). Petrochemicals New Build and Expansion Projects Analysis: https://www.researchandmarkets.com/reports/5742372.

2.3 Waste to Energy

Waste-to-energy (WtE) refers to a group of technologies that convert waste materials into usable energy forms, primarily through thermal incineration with energy recovery (Alao et al., 2022). This approach aims to mitigate reliance on landfills, foster the generation of renewable energy, and potentially reduce greenhouse gas emissions when compared to traditional landfill practices lacking methane capture mechanisms. WtE may present itself as an alternative method for managing waste while contributing to energy generation; however it must be seen as a last step to be taken, when reduce, reuse or recycle are no longer possible or viable (Lisbona et al., 2023).

Modern WtE facilities have advanced in terms of emission controls, but continuous stringent monitoring remains critical to mitigate pollution risks, including dioxins and heavy metals. The greenhouse gas impacts of WtE, although potentially lower than non-methane capturing landfills, still necessitate a comprehensive assessment against other waste management options (Pfadt-Trilling et al., 2021), and overreliance on WtE can inadvertently discourage efforts towards upstream waste prevention.

Diverse perspectives characterize the debate around WtE. The efficiency of the processes is highly dependent on the characteristics and the calorific value of waste, posing challenges for waste streams with high moisture or non-combustible content. Furthermore, the high capital and operational costs associated with WtE, coupled with the risk of a "lock-in" effect—where a continuous stream of waste is required for financial viability—demands a careful cost-benefit analysis to ensure it does not undermine waste reduction efforts at the source (Pfadt-Trilling et al., 2021). Advocates highlight the technology's potential for landfill diversion, especially in regions where land is scarce, and its contribution to energy generation, mainly where renewable options are limited. Improvements in emissions control technologies also suggest that WtE can reduce environmental impact when facilities are well-managed. However, critics raise concerns about WtE's potential to detract from waste reduction and recycling efforts, its net contribution to greenhouse gas emissions, and the financial risks associated with its high costs and dependency on consistent waste streams. Health concerns related to emissions, even with modern technology, further complicate public acceptance and underscore the need for ongoing scrutiny (Lisbona et al., 2023).

Waste-to-energy (WtE) technologies, such as incineration, gasification, and pyrolysis, can play a crucial role in converting waste into usable forms of energy, aligning with strategic goals to reduce reliance on landfills and avoid leakage. However, to optimize the integration of WtE into waste management strategies, it is essential to consider its placement within the waste hierarchy, balance priorities to avoid hindering waste reduction efforts, mitigate environmental impacts through stringent monitoring, conduct cost-benefit analyses to ensure financial viability without undermining waste reduction at the source and foster community engagement for transparency and alignment with sustainability goals. (UNEP, 2019).

2.4 Carbon Neutrality and Plastic Pollution

The imperative of achieving carbon neutrality by 2050 highlights the battle against climate change, driven by greenhouse gas (GHG) emissions from fossil fuel combustion since the Industrial Revolution (Saunios et al., 2019). The escalating atmospheric CO2 concentration has reached critical levels, exacerbating global warming and its associated catastrophic consequences, including extreme weather events, sea-level rise, and biodiversity loss. Carbon neutrality entails not only reducing emissions to levels that the Earth's forests and oceans can naturally absorb but also implementing technological and policy measures to eliminate or offset the remaining emissions. This equilibrium is vital for stabilizing global temperatures and mitigating the most severe impacts of climate change.

The pathway to carbon neutrality requires concerted efforts across all sectors of society, including governmental, corporate, and individual actions (UNEP, 2020). The UN has emphasized the need for a global coalition supporting carbon neutrality, aligning financial systems with climate goals, and enhancing climate change adaptation and resilience. Achieving carbon neutrality involves transitioning to net-zero emissions through policies that include carbon pricing, ceasing the construction of new coal plants, shifting the tax burden from taxpayers to polluters, and integrating carbon neutrality into financial and fiscal planning.

Despite the challenges outlined above, there are promising opportunities to leverage in the plastic management domain. Embracing a circular economy for plastics holds significant potential to reduce the necessity for virgin plastic production. Prioritizing fundamental shifts – Reuse, Recycling, and Reorientation and Diversification– can markedly decrease plastic waste generation and associated greenhouse gas emissions across production and end-of-life phases. Exploring renewable energy integration in waste management presents another avenue for progress. Utilizing renewable sources like solar and wind power to fuel recycling and waste processing facilities can diminish their carbon footprint.

Moreover, capturing biogas from landfills and converting it into renewable energy further reduces reliance on fossil fuels, aligning waste management practices with carbon neutrality objectives (Zheng et al., 2019). Furthermore, advancements in material science offer promising avenues for reducing overall emissions and moving closer to carbon neutrality (Chen et al., 2024, Wang et al., 2021). The studies by Zheng et al. and Wang et al. represent a growing body of evidence supporting the adoption of bioplastics. Developing and adopting biodegradable bioplastics and recycling plastics may represent the best opportunities for decreasing the carbon footprint of virgin plastics. Table 3 offers a concise comparison between bioplastics and fossil fuel-derived plastics.

Feature	Bioplastics	Petrochemical Plastics
Biodegradability	Biodegradable under specific conditions, varying based on material type	Generally non-biodegradable, leading to long-term environmental pollution
Carbon Footprint	It can be carbon neutral due to bio-based origin and biodegradability	It can be carbon neutral due to its bio-based origin and biodegradability

Energy Efficiency	Production may require less energy compared to petrochemical plastics	Production tends to be more energy-intensive
Unique Properties	Unique properties based on material composition and processing methods; durability and resistance tends to be lower	Known for their durability and resistance, but lack the biodegradability of bioplastics
Versatility	Used in various industries like automotive and biomedical	Dominate different sectors but offer limited versatility
Examples	PHA, PLA, PHB, Cellulose-based, Starch-based, Protein-based, Lipid-based	HDPE, LDPE, PET, PVC, PS, PP
Market Potential	Growing market potential due to increasing demand for sustainable alternatives	Established market presence but facing pressure to adopt more sustainable practices
Environmental Impact	Overall, lower environmental impact due to biodegradability and renewable sourcing	Overall, higher environmental impact from non-biodegradable nature and reliance on fossil resources

Table 3. Comparison between Bioplastics and Petrochemical Plastics
Source: (Nanda et al., 2021)

Other interventions include minimizing plastic use, enhancing recycling, and exploring advanced waste treatment technologies to achieve a sustainable future. Strategies to reduce plastic use include promoting the adoption of reusable products, re-designing products for recyclability, and consumer education to reduce unnecessary plastic consumption (Fletcher et al., 2023). The planned expansion of plastic production could see emissions reach 1.34 gigatons annually by 2030, equivalent to nearly 300 new coal-fired power plants (Vallette, 2021). According to Vallette, by 2050, plastic production alone could consume 10-13% of the world's remaining carbon budget. This trend stems from fossil fuel dependence throughout the plastic lifecycle, from extraction to waste management, with harmful emissions released at each stage.

Case Study: How Waste Becomes Hydrogen Mobility in Wuppertal (Risco-Bravo et al., 2024)

Project: Power-to-Gas for hydrogen production at the MHKW Wuppertal
Location: Wuppertal, Germany
Goal: Develop a sustainable transportation system using hydrogen produced from waste-to-energy.

Key elements:

- *Construction of a hydrogen filling station at the waste incineration plant.*
- *Use of hydrogen fuel cell buses and garbage trucks.*
- *Reduction of nitrogen oxide emissions and improvement of air quality.*

Results:

- *325 kg of daily hydrogen demand met by the waste-to-energy plant.*
- *Potential for tripling hydrogen production capacity.*
- *Winner of the Stadtwerke Award 2019 from the VKU.*

Benefits:

- *Reduced reliance on fossil fuels.*
- *Improved air quality.*
- *More sustainable waste management.*

Challenges:

- *High initial investment costs.*
- *Need for public and private sector collaboration.*

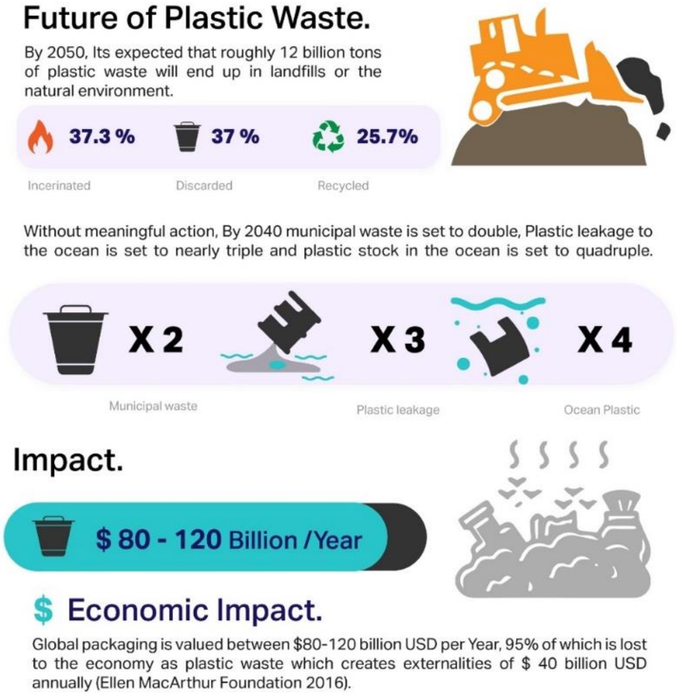
Future:

- *Expansion of hydrogen production and refuelling infrastructure.*
- *Development of additional hydrogen-powered vehicles.*

This case study demonstrates the potential of using waste-to-energy to produce hydrogen for transportation. The Wuppertal project is a successful example of how this technology can be implemented to reduce emissions and improve air quality.

3. Chapter Three: Social and Economic Aspects of Plastic Waste Management

Plastic waste management is a multi-dimensional challenge with far-reaching social and economic implications. As the production and consumption of plastic products continue to escalate globally, societies face the challenge of addressing the environmental repercussions while navigating the complexities of recycling, disposal, and reduction strategies, where social behaviours, policy frameworks, technological advancements and market dynamics all intertwine. These elements collectively influence the effectiveness and viability of waste management strategies and their adoption by societies. This chapter aims to paint a picture of plastic waste management's social and economic aspects, vital for devising comprehensive strategies that align with environmental goals, towards a more sustainable and resilient future.



By 2050, Its expected that roughly 12 billion tons of plastic waste will end up in landfills or the natural environment.

Without meaningful action, By 2040 municipal waste is set to double, Plastic leakage to the ocean is set to nearly triple and plastic stock in the ocean is set to quadruple.

Global packaging is valued between $80-120 billion USD per Year, 95% of which is lost to the economy as plastic waste which creates externalities of $ 40 billion USD annually (Ellen MacArthur Foundation 2016).

Figure 3-1. Future Economic Impact of Plastic Waste in a Business-as-Usual Scenario
Source: (OECD, 2023)

Figure 3-1 illustrates the projected consequences of continued plastic waste generation and its financial implications. By 2050, it is estimated that 12 billion tons of plastic waste will accumulate in landfills or the natural environment. This scenario forecasts a significant economic impact, with an estimated cost of $80 to $120 billion per year. Additionally, plastic pollution is anticipated to create external costs of $40 billion annually, reflecting the broader impact on the global economy and environment. The data, sourced from the 2016 Elen Mcarthur Foundation report ‘Rethinking the future of plastics’ underscores the urgent need for addressing the plastic waste crisis to mitigate its economic and ecological repercussions (Agenda, 2016).

3.1 Impact on Coastal Communities

Marine plastics can diminish the productivity and efficiency of fisheries and aquaculture, directly threatening vital food sources such as fish and shellfish, which are integral to the diet of over a billion people globally(Narwal et al., 2024). The impact of marine plastics extends beyond food provision to encompass cultural and experiential values associated with marine wildlife and recreational activities. Charismatic marine species, such as seabirds, turtles, and cetaceans, suffer from entanglement and ingestion of plastics, which has consequences for both animals and human well-being(Le et al., 2024). Charismatic sea animals like dolphins, whales, and seals have been demonstrated to positively impact mental health by evoking awe, fostering a connection to nature, and promoting mindfulness. However, captivity-related ss and environmental challenges contribute to their decline, affecting both animal well-being and causing distress among conservationists (Bruder et al., 2022). Furthermore, marine plastics adversely affect experiential recreation, as litter on beaches and coastal areas deters visitors, resulting in economic losses for local communities and negative impacts on individuals' physical and mental health. This disruption of recreational enjoyment underscores the broader economic and social costs of marine plastic pollution.

3.2 Economic Challenges for Creating a Circular Plastics Economy

3.2.1 New Petrochemical Investments & Long-Term Emissions

The international petrochemical sector is anticipated to allocate approximately $400 billion towards the construction of new facilities from 2020 to 2025, as reported by the United Nations Environment Programme (2023) and echoed in industry publications such as Platts (2023) and Chemical & Engineering News (2023). These substantial investments underscore the ongoing reliance on fossil-fuel-based plastics and the looming threat of carbon lock-in. The IEA estimates that 45% to 95% of the future oil demand could be driven by the petrochemical industry (International Energy Agency, 2023; BP, 2023), potentially leading to stranded assets should the production of fossil fuels diminish in the pursuit of net-zero emissions targets (McGlade et al., 2019). Establishing new petrochemical infrastructure, given the average plant lifespan of 10-15 years and operational capabilities extending over 30 years (Plastics Europe, 2023) may hinder the shift towards alternative, non-fossil plastic feedstocks (Geyer et al., 2020).

3.2.2 Price Competitiveness of Bio-Derived Plastics

Despite accounting for over 400 million tonnes of annual production, bioplastics constitute less than 1% of the total plastic output (Ellen MacArthur Foundation, 2022). This significant discrepancy is primarily due to the cost disparity, with biopolymers being up to three to four times more expensive than fossil-fuel-based plastics (Biopolymer Market Research Consultants, 2023). The cost advantage enjoyed by petrochemical plastics arises from various factors, including:

Petrochemical Advantage: Plastics derived from fossil carbon are by-products of oil and gas extraction, resulting in an abundant and comparatively inexpensive feedstock supply. (International Energy Agency, 2023).

Maturity of the Petroleum Industry: The petroleum industry benefits from a well-established business model and two centuries of development, achieving cost reductions through scale economies (BP Statistical Review of World Energy, 2023).

Fossil Fuel Subsidies: Governmental subsidies further diminish the costs associated with fossil-based plastics (Coalition for Rainforest Nations, 2023).

Elevated Bio-Feedstock Costs: In contrast, bioplastic alternatives face higher feedstock expenses relative to the abundance of fossil fuels (World Bank, 2023).

In addition, in the cases where few bio-derived plastics managed to be price-competitive, limitations such as inadequate composting and recycling infrastructure impede their widespread adoption (Bioplastic Market Research Consultants, 2023).

3.3 Digital Trading in Recycled Plastics

Innovative digital platforms are emerging as pivotal tools for facilitating information exchange within the recycled plastic market, mirroring the role of digital platforms in enhancing circularity and material efficiency across both formal and informal economic sectors. Notable examples include Circular (US), Surplus (Germany), and Circularise (Netherlands), which offer platforms for the quality-controlled exchange of recycled plastics, catering to large corporations in search of increased recycled content. These platforms endeavour to reconcile the demand and supply discrepancies in the recycled plastics market. Furthermore, initiatives like Plasticbank® integrate informal waste collection and recycling activities with global market demands, embedding social and developmental considerations within the recycled plastic economy (Plastic Bank, 2023). A study in Indonesia highlights the potential of digitalization to bolster resource recovery and employment opportunities in managing non-biodegradable waste (Ntiamoah et al., 2023).

3.4 The Economic benefits of systems change in plastic waste management.

A seminal 2020 report by the Pew Charitable Trusts and SystemIQ - "Breaking the Plastic Wave," presents a compelling roadmap for drastically curtailing plastic pollution[1]. The analysis reveals that through the systematic implementation of eight targeted interventions, a reduction of plastic pollution by 80% by 2040 is achievable. This ambitious yet feasible pathway contrasts the projected tripling of plastic pollution under the current "business-as-usual" trajectory. The report highlights the compelling economic rationale for transitioning to a more sustainable plastics system. Conversely, the "systems change" approach demonstrably offers immediate cost reductions and significant cumulative savings over the next two decades.

According to the publication, by 2040, the systems change scenario holds the potential to:

- Generate annual cost savings ranging from USD 130 billion to USD 200 billion. This substantial economic benefit originates from a confluence of factors, including reduced production costs, minimized operational expenses, and increased revenue streams generated through the recovery and reintegration of recycled materials.
- Achieve a net cost reduction of 10%. This reduction is contingent upon a strategic combination of decreased capital expenditure, optimized operational costs, and enhanced revenue generated through efficient recycling infrastructure and processes.
- Avert USD 3.3 trillion in societal damages (externalities) associated with plastic pollution. These externalities encompass a broad spectrum of deleterious effects, including ecological harm to marine ecosystems and potential human exposure to hazardous chemicals. Abating 45% of the total plastic life cycle cost projected under the BAU scenario.

Efforts focused on reducing plastic production and processing levels, alongside a strong emphasis on recycling, would result in a notable 10% decrease in investment, operational, and management costs throughout the plastic life cycle. Furthermore, by effectively addressing environmental damage and potential health risks linked to plastic pollution, the adoption of a systems change approach prevents an estimated USD 3.3 trillion in externalities. Signifying a significant economic advantage compared to the Business-As-Usual (BAU) scenario. The findings from the Pew report underscore the critical importance of transitioning the current plastics system towards a more sustainable model.

3.5 Social Inclusion in Waste Management Systems

Conventional waste management systems frequently neglect or insufficiently cater to the requirements of marginalized and underserved communities. Addressing the plastic industry's environmental impact within the context of global climate goals requires inclusive waste management systems that cater to everyone, regardless of socioeconomic status or location (Rutkowski et al., 2020). Active engagement of citizens in sharing the responsibility for waste management is critical; however, public engagement has its challenges.

One of the primary challenges for inclusive waste management lies in ensuring efficient and accessible waste collection services in underserved communities. Often, these areas lack the necessary infrastructure, such as regular waste collection routes and designated disposal sites. This results in illegal dumping, open burning, and uncontrolled waste accumulation, posing significant health and environmental risks for residents (Robinson, 2011). Decentralized waste management systems, with micro-transfer stations closer to waste sources, could improve the efficiency and accessibility of waste collection in dense urban areas. (Cointreau, 2006). In rural settings, promoting community-based initiatives, such as composting and decentralized biogas production, can offer sustainable and culturally sensitive solutions (Oteng-Ababio et al., 2013).

3.6 Fostering Public Participation in Waste Management

In waste management, inclusivity goes beyond service access to encompass active public involvement in decision-making and implementation processes. Traditional top-down approaches often overlook the diverse needs and obstacles faced by different communities. Engaging citizens directly allows authorities to gather valuable insights for developing culturally appropriate, efficient, and sustainable waste management strategies. Establishing platforms for community dialogue, context-specific awareness campaigns, and training programs to enhance residents' waste management skills is essential for fostering such participation (Robinson, 2011). Research highlights the effectiveness of this approach; for example, participatory slum upgrading initiatives in India integrating waste management solutions have significantly enhanced hygiene and local well-being (Rao et al., 2020).

Public engagement plays a crucial role in fostering inclusivity and transparency in waste management. This approach involves transparent discussions, inclusive workshops, and partnerships with local leaders and organizations to align waste management efforts with community values and priorities. Case studies from India and Brazil highlight the benefits of community involvement in waste management initiatives. Overcoming challenges such as limited resources, political will, trust issues, and resistance to change is essential for promoting inclusivity and transparency in waste management endeavours, emphasizing the significance of inclusive and transparent public engagement, education, and collaboration in addressing waste management challenges effectively while ensuring diverse stakeholder participation for sustainable solutions.

3.7 Revolutionizing the Global Job Market through a Circular Economy

In ground-breaking findings, the International Labour Organization (ILO) and the Organisation for Economic Co-operation and Development (OECD) have unveiled divergent yet transformative forecasts for job creation within the circular economy by 2030. Global studies by ILO (2018) and OECD (2020) project net job creation in a circular economy, though with differing magnitudes (7-8 million vs. 1.8 million by 2030).

Projecting a significant boost to global employment, the ILO estimates 7-8 million new jobs within the circular economy framework by 2030. According to the ILO, this upswing and several factors could drive significant job creation within the circular economy framework, potentially adding 7-8 million new jobs globally by 2030. These factors include a booming demand for labour in recycling and reprocessing industries, a dynamic shift towards community-rooted service sectors focusing on maintenance, repair, and reuse, and the overall expansion of the 'green economy' concentrate on renewable energy and sustainable infrastructure.

OECD's Calculated Forecast predicts a more measured, yet significant, net increase of 1.8 million jobs globally. This projection recognizes the shifting landscape of job losses in traditional sectors like mining, counterbalanced by emerging opportunities in innovative secondary material production and reprocessing, particularly in high-value materials. Additionally, there is significant growth in waste management and resource efficiency industries, which are crucial for sustainable resource utilization. Complementing these developments is a renaissance in innovation and research, sparking new career paths for experts in various fields.

The variation in job creation projections from the ILO and OECD is due to their different methods and focus points. The ILO uses a wide-ranging scenario analysis, considering numerous possible future scenarios, whereas the OECD relies on precise, computable general equilibrium models for specific forecasts. Both projections rely on varying assumptions regarding economic trends, technological progress, and policy shifts. The ILO focuses on job growth in developing countries, while the OECD looks at employment opportunities in developed nations, pointing to significant global differences in job growth expectations. These forecasts mark an initial step towards understanding the complex link between the circular economy and employment, highlighting the need to address critical issues such as fair job distribution, skill gaps, and the necessity for policies protecting vulnerable groups. Although the number of jobs the circular economy will create is unclear, the ILO and OECD studies underscore its vast potential to reshape the employment landscape. Delving into the nuances of these predictions and addressing their broader challenges is crucial for steering our planet towards a sustainable, employment-rich future. Transformation through

3.8 Reuse and Refill culture and its role in social inclusion.

The emergence of a carbon-neutral world will shift attitudes towards plastics. A new approach centred on reuse and refill systems will transform consumption habits and minimize product environmental footprints. Reusable containers dispensing everything from laundry detergent to cleaning fluids will become the preferred packaging once packaged in plastic. Bulk dispensers for grains, legumes, and staples at significant cost savings while eliminating plastic packaging waste will transform shopping habits. The Ellen MacArthur Foundation's 2019 prediction of lower consumer costs through reduced plastic packaging will materialise, becoming a tangible reality in households across the globe.

However, the benefits extend far beyond affordability and convenience. Food rescue programs play a crucial role in this circular economy, intercepting perfectly edible food destined for landfills and redistributing it to those in need. Parfitt et al. (2016) noted that these programs address food insecurity and actively promote sustainability by diverting waste from landfills, including mountains of discarded plastic packaging. In a net-zero world, this synergistic interplay between environmental responsibility and social welfare reaches its full potential, ensuring secure access to nutritious food and safeguarding the planet by minimizing plastic waste and carbon footprint.

This vision transcends traditional waste management, painting a picture of a seamlessly integrated system where resource efficiency fosters economic inclusivity and environmental sustainability. Reuse and refill are no longer fringe movements; they have become the guiding principles for a future where cost-effective consumption and environmental responsibility are intrinsically linked, particularly regarding our use of plastics.

3.9 Community Engagement for Sustainable Plastic Waste Management

Sustainable plastic waste management and a circular plastics economy will require more than technological advancements; it will rely on active community engagement, necessitating a participatory approach and citizen education (Brotosusilo et al. 2020).

Participatory Design and Implementation: Communities must be integral to shaping the solutions. Facilitating open dialogue platforms, citizen co-creation workshops, and inclusive decision-making processes fosters ownership and ensures waste management strategies align with local needs and cultural contexts. UNEP reports highlight the success of initiatives in India and Indonesia, where waste pickers were actively involved in designing new waste collection systems, leading to improved efficiency and social inclusion (Hernández et al., 2024).

Education and Capacity Building: Beyond simply informing citizens about the environmental harms of plastic, targeted education initiatives empower them to act as responsible stewards, including the promotion of waste reduction and reuse practices at individual and household levels, raising awareness about proper sorting and recycling protocols, and fostering skills development for local entrepreneurs interested in circular economy ventures. The World Resources Institute's (WRI) "Cities Rethinking Plastic" project demonstrates the effectiveness of such initiatives, with tangible reductions in plastic waste reported in participating cities due to comprehensive awareness campaigns and community-driven action plans.

Leveraging Local Knowledge and Networks: Community engagement should also embrace the wealth of local knowledge and existing social networks (Phan et al., 2022). Indigenous communities, for instance, often possess traditional waste management practices with immense potential for adaptation and integration into modern systems. Additionally, harnessing the power of local faith-based organizations, civil society groups, and youth networks can amplify outreach and encourage collective action. As a study by the Stockholm Environment Institute suggests, such collaborative efforts can foster a sense of environmental stewardship and create lasting change within communities (SEI, 2021). Building a sustainable future is not a top-down endeavour; it requires the collective voices and active participation of communities at every step. By nurturing this engagement and unlocking the power of local knowledge, we can collectively forge a sustainable path towards a world free from plastic pollution.

3.10 Gender-Responsive Policies in Plastic Waste Management

Achieving a sustainable plastics future necessitates a nuanced understanding of the intricate interplay between social and environmental factors within plastic waste management systems (Kandpal et al., 2023). Technological advancements and sustainability goals hold promise for the plastics crisis, but their effectiveness hinges on addressing gender dynamics. A genuinely successful strategy requires more than just equal participation. It demands embedding gender-responsive policies and safeguards throughout the entire plastic value chain.

The initial step requires recognizing the gendered dimensions of plastic waste management. Women often bear the brunt of informal and hazardous waste collection and recycling efforts, highlighting the need for policy frameworks that transcend mere inclusion and aim for transformative change (Kandpal et al., 2023). Formalizing the waste management sector is crucial for the safety and well-being of female workers by providing proper equipment, implementing safety measures, and ensuring access to social protections and decent work conditions. The International Labour Organization's (ILO) efforts in Indonesia and Ghana, which led to improved working conditions and increased female participation in formal waste management systems, serve as powerful examples of the impact of such measures (Buckingham, 2020).

Furthermore, gender-responsive policies must address the unequal distribution of knowledge and resources for plastic waste management. Women from marginalized communities often face barriers to accessing information and training on efficient waste management practices (Hong et al., 2018). Addressing this disparity requires targeted awareness initiatives, capacity-building programs sensitive to gender and cultural nuances, and the development of technology accessible to women. Research from the UNEP-IETC on Ghana's gender-tailored waste management training programs highlights the success of these approaches in elevating recycling rates and fostering micro-enterprises dedicated to waste recovery and reuse[24].

Increasing the contribution and entrepreneurship of women is crucial for cultivating a sustainable and equitable plastic waste management ecosystem. Encouraging women-led initiatives in waste collection, recycling, and upcycling can drive economic empowerment and local innovation. Government support is critical in providing access to micro-financing, facilitating market connections, and implementing gender-inclusive procurement policies (Kandpal et al., 2023).

To enhance the role of women, creating a gender action plan consistent with national gender policies is essential (Chant & Pedwell, 2008). Such a plan firmly integrates gender roles, including responsibilities, time allocation, and the distribution of access and control over resources and decision-making processes within critical sectors such as the government, marketplaces, communities, and families. Following this, it is crucial to identify obstacles that prevent equal participation throughout the value chains and to classify the roles of women in these sectors as regulators (policymakers), market actors (business owners), workers, end-users (consumers), and community members. Allocating a budget dedicated to initiatives aimed at driving significant changes toward equality will maximize the potential of communities and pave the way for a world where all share the benefits of a sustainable environment in efforts like eliminating plastic waste.

4. Chapter Four: Scenarios for Plastic Waste Management

As society approaches the pivotal year of 2050, it faces a critical crossroads in the pursuit of a carbon-neutral future. The realities of technological maturity temper the aspiration of a fully circular plastic economy, the investment landscape within the fossil fuel industry, and the complexities surrounding bioplastics. The enduring legacy of plastic pollution presents a spectrum of scenarios with varying degrees of reliance on fossil fuel-derived and bio-plastics.This section tentatively explores four distinct scenarios, outlined in Table 2 below, that highlight potential pathways and challenges towards a sustainable future for plastic waste management within a carbon-neutral framework. The analysis encompasses the Business as Usual (BAU), The Circular Revolution (CPR), Community-Driven Waste Management, and the Hybrid Framework scenarios, each presenting unique approaches to plastic consumption, waste management, and climate change mitigation. These scenarios aim to delineate plausible directions for socially and economically sustainable plastic waste management while also addressing the environmentally sound management of other waste streams.

Scenario	Description	Key Features	Implications for Climate Change	Opportunities & Challenges
Business as Usual (BAU)	Persistence with linear lifecycle models and conventional end-of-life treatments.	Increased plastic consumption, limited advances in recycling, reliance on fossil fuels and landfills.	Exacerbated global warming, ecosystem damage, and public health issues.	Limited opportunity for improvement highlights the need for systemic change.
The Circular Revolution (CPR)	Complete transformation to a dominant circular economy with net-zero carbon emissions.	Compostable bioplastics, chemical recycling, pyrolysis, closed-loop systems, minimalist consumption, and increased renewable energy.	Significant reduction in greenhouse gas emissions and enhanced carbon sequestration.	Requires innovation, collaboration, and behavioural change but offers the potential for significant sustainability gains.
Community-Driven Waste Management	Focus on community engagement and leadership to tackle plastic waste. Government programmes are inadequate to meet all waste management needs.	Strong community involvement, holistic waste management, accessible infrastructure, and motivational incentives. Localised circularity	Reduced plastic use and emissions through local action empower communities to be agents of change.	Requires education, resources, and sustained public participation but fosters collective responsibility and ownership.
Hybrid Framework	This transitional phase uses both fossil fuel-derived and bioplastics strategically.	Slower uptake of Advanced recycling, CCU (Carbon Capture and Utilization) technologies, moderately responsible resource allocation, and market diversification with sustainable choices.	Potential for emissions reduction and resource efficiency but requires careful management to avoid unintended consequences.	Balances immediate needs with long-term goals necessitate collaboration and regulatory frameworks for a smooth transition.

Table 2. Summary of Scenarios for Plastic Waste Management in a Carbon-Neutral Society

4.1 Scenario One: Business as Usual (BAU)

The Business-as-Usual (BAU) scenario perpetuates a linear plastic lifecycle with conventional end-of-life practices(Fletcher et al., 2023; Lau et al., 2020; Vidal et al., 2024). It assumes no significant increase in recycling, plastic consumption rising to 1.1 Gt by mid-century, and only modest improvement in waste management (43% recycling, 50% incineration, 7% landfill). While acknowledging the need for change, BAU's reliance on post-consumer recycled (PCR) content raises concerns about collection and sorting infrastructure, as well as PCR material quality and suitability (Geyer et al., 2017). Furthermore, BAU overlooks innovations like bioplastics, renewable energy, and CCU, which are crucial for reducing the plastics sector's carbon footprint and shifting towards circularity (Kaza et al., 2018). Ultimately, the BAU scenario offers only incremental adjustments within a fundamentally unsustainable system, emphasizing the need to move beyond BAU towards systemic changes that embrace circularity and decarbonization for managing plastic waste.

4.1.1 Key Features

The global reliance on fossil fuel-based plastic continues despite mounting warnings. Annual consumption exceeding 1.5 billion tons, fuelled by population growth and rampant consumerism, generates a deluge of waste, particularly single-use plastics. Strained waste management systems struggle to keep pace, resulting in low to moderate recycling rates, overflowing landfills spewing pollutants and greenhouse gases, and increasingly common, yet polluting, incineration. This crisis spills over into our oceans, where millions of tons of plastic leak annually, jeopardizing marine life and introducing microplastics into the food chain, potentially impacting human health. Plastic production, heavily reliant on fossil fuels, further exacerbates climate change by pushing carbon emissions upwards, while landfills contribute their share of methane. The economic and social consequences are dire, with coastal communities suffering from crippled tourism and fisheries and healthcare systems burdened by pollution-related health issues. Despite growing awareness, international efforts and innovative solutions like advanced recycling technologies and circular economy principles remain limited by economic, regulatory and political hurdles.

4.1.2 Implications for Climate Change

The fossil fuel dependence on plastic production elevates greenhouse gas emissions, amplifying global warming and extreme weather events. Landfills and inefficient incineration contribute further, releasing potent pollutants and methane. Marine plastic disrupts essential ecosystems, hindering their capacity to sequester carbon and exacerbating ocean acidification. The adverse ripple effects of plastic pollution led to resource depletion, socioeconomic instability, and conflict, further complicating climate mitigation efforts.

4.1.3 Opportunities and challenges

Conversely, the scenario provides the impetus towards a circular economy. Increased uptake of bioplastic and reusables opens new markets and diminishes the reliance on conventional plastics. Advances in recycling technologies and circular economy principles, such as enhancing product longevity, reusability, and minimizing waste, present viable solutions for reducing environmental impacts. Integrating cleaner production methods and renewable energy can significantly lower the carbon footprint of plastics. Moreover, fostering international collaboration, sharing knowledge, and implementing unified regulations are crucial for advancing sustainable plastic management. Cultivating consumer awareness and promoting a culture of environmental responsibility are vital to driving demand for eco-friendly products. This scenario highlights the stark choices between continuing the BAU path, which risks irreversible environmental damage and seizing the opportunity for innovation, collaboration, and systemic change towards a sustainable and circular plastics economy.

4.2 Scenario Two: The Circular Revolution

The Circular Plastics Revolution (CPR) is where society achieves net-zero carbon emissions. Buildings rely on efficient, decarbonized energy mixes powered by renewable sources. Society views waste as a resource, and closed-loop systems regenerate plastic materials, ensuring they remain in circulation at the highest possible quality. When a material is not viable to create a new product, it becomes compost. This model embraces simplicity and sustainability as core values.

The world economy departs from the "take, make, dispose" model, transforming through resource efficiency and dematerialized processes. Society meticulously designs, produces, and uses every product. Environment-related footprint becomes a crucial metric in the cradle-to-cradle design approach, guiding decisions on products and services. Society uses Lifecycle Analysis (LCA) principles to minimize environmental impact at every stage. Extended Producer Responsibility (EPR) ensures manufacturers take full accountability for their product's environmental impact throughout their entire lifecycle. Durability and repairability replace planned obsolescence as core product design principles.

In the CPR's new plastics economy, conspicuous consumption gives way to a minimalist approach focused on a closed-loop system. Here, society repurposes or recycles used items rather than discard them. Biomaterials derived from renewable resources increasingly replace fossil fuel-based materials. This shift reflects a growing recognition that actual value lies in the quality and sustainability of goods rather than quantity. This section delves into the primary interventions, opportunities, and challenges associated with this shift, demonstrating how society can turn the theoretical concepts of simplicity and sustainability into practical realities.

4.2.1 Key Features

To create a sustainable future for plastics, an integration of innovations in material science, design philosophies, consumer behaviour, and policy frameworks. New biomaterials with enhanced recyclability and durability, alongside compostable bioplastics for home use, lessen reliance on single-use plastics and accelerate circularity. Closed-loop systems emphasizing repairable goods and a sharing culture will reduce consumption while reusing plastic waste for textiles showcases resource value retention within urban settings. Waste prevention through cradle-to-cradle design and the transformation of organic waste into resources will underpin regenerative urban systems fuelled by biomimetic architecture and green spaces. By 2050, sustainable alternatives to fossil fuel-based polymers -e.g., made from algae and agricultural waste designed for disassembly and advanced recycling- will virtually eliminate plastic pollution. This transition relies upon a cultural shift towards minimalism, prioritizing experiences over ownership, and a preference for recycled or bio-based materials. Community-driven refill stations and repair shops will combat single-use packaging and extend product lifespans, while intelligent packaging and biodegradable polymers point towards a waste-free future. Digital technologies will enable traceability and resource optimization, and customized LCA tools will guide minimal-impact eco-design. Enhanced global EPR, an innovation fund, adaptive regulations, and incentives will drive this transformation. Zero-carbon manufacturing using renewable energy and carbon capture will achieve carbon neutrality in the plastics sector, enabled by cross-sector collaborations that maximize impact.

4.2.2 Implications for Climate Change

The CPR scenario significantly benefits climate change mitigation by reducing greenhouse gas emissions and enhancing carbon sequestration. Emphasizing the use of recycled and bioplastic plastics minimises the dependence on fossil fuels, thereby decreasing emissions from extraction, refining, and processing. Improvements in recycling and composting, alongside initiatives like right-to-repair and reusable packaging, contribute to minimizing emissions from landfills, incineration, and the overall product lifecycle. Additionally, promoting widespread composting of organic waste creates nutrient-rich soil that sequesters carbon, while responsibly managed bioplastics from renewable sources can further enhance carbon capture through plant growth.

4.2.3 Opportunities and challenges

Building a sustainable plastic ecosystem demands a multifaceted approach, requiring synchronisation of e innovations in material science with eco-design, consumer behaviour changes, and robust policy frameworks. Challenges include finding the right balance between new materials and existing design preferences, overcoming entrenched consumer habits, resolving technical limitations of biomaterials, and ensuring effective policy implementation.

Despite the obstacles, this coordinated effort unlocks critical opportunities. Biomaterials and closed-loop systems can help curb single-use plastics, pollution, and environmental damage. It fosters green jobs in multiple sectors, improves urban spaces through waste conversion and biomimetic design, allows tech-driven eco-design advancements, and transitions the plastics sector towards carbon neutrality. These actions are essential for a sustainable future. Building a sustainable plastic ecosystem demands a multifaceted approach. We must synchronize innovations in material science with thoughtful design, consumer behaviour changes, and robust policy frameworks. Challenges include finding the right balance between new materials and existing design preferences, overcoming entrenched consumer habits, resolving technical limitations of biomaterials, and ensuring effective policy implementation.

4.3 Scenario Three: Community-Driven Waste Management

In the year 2050, communities have taken the lead in revolutionizing waste management practices. Recognizing the inadequacy of public authorities in addressing waste management challenges, grassroots movements initiated by communities have stepped in to bridge the gap. This shift is driven by a profound awareness of the detrimental impacts of plastic pollution and a resolute commitment to safeguarding a cleaner environment for future generations. Across towns and cities, vibrant community recycling centres have replaced overflowing landfills, efficiently sorting materials for reuse, repair, and responsible recycling. In tandem, community gardens thrive, nourished by nutrient-rich soil produced from composted plastics, exemplifying a closed-loop system in operation. While this vision may have appeared overly ambitious in the past, collective dedication has made it the new norm. By studying communities that embraced the transition to sustainability early on, invaluable insights have been gleaned, paving the way for enduring sustainable transformations. These insights serve as a testament to the transformative impact that engaged communities have in creating lasting environmental legacies.

4.3.1 Key Features

Community engagement and leadership are central to effective plastic waste reduction. Communities actively organize initiatives that involve residents in sustainable practices, fostering a culture of responsibility and long-term commitment. This participatory model combines educational campaigns, awareness initiatives, and volunteerism to empower residents to reduce plastic use directly. It also promotes a broad waste management strategy encompassing reduction, reuse, recycling, composting, and upcycling. Community recycling centres, collection drives, and upcycling workshops provide accessible infrastructure, while incentive programs based on credits and compensations offer rewards redeemable at local businesses, further motivating participation and strengthening the local economy. These integrated actions cultivate a culture of sustainability, ensuring that waste reduction efforts become deeply ingrained within the community for lasting impact.

4.3.2 Implications for Climate Change

Mitigating the climate impact of plastic waste requires a multifaceted strategy that includes reducing new plastic production, enhancing recycling processes, composting biodegradable plastics, and overhauling waste management infrastructure. By decreasing the reliance on new plastics and improving recycling, the overall carbon footprint is reduced. Composting biodegradable plastics contributes to soil enrichment, which in turn increases the soil's capacity for carbon sequestration. Modernizing waste management infrastructure can reduce landfill dependency, thereby cutting down methane emissions, a potent greenhouse gas. Empowering communities and individuals **to steward the environment actively** is central to these efforts. Such empowerment offers practical ways to engage in climate solutions, promoting a widespread movement towards a sustainable and climate-resilient future.

4.3.3 Opportunities and Challenges

Community based strategies not only stimulate local economies but also offer safer and more sustainable jobs compared to traditional waste management roles. These jobs range from waste collectors to recycling technicians and entrepreneurs, catering to a diverse set of skills and interests within the waste management sector. The emphasis on zero-waste approaches aligns with the traditional waste hierarchy, showcasing that economic and environmental goals are compatible. Repair, recycling, and remanufacturing create significantly more jobs compared to landfilling or incinerating waste, with zero waste systems creating better quality jobs in terms of wages, working conditions, and skill development potential. The shift towards zero waste not only creates more jobs but also fosters stronger and healthier communities by promoting sustainable practices and reducing environmental impacts.

Caste Study: Wangwa Community sustainable waste management initiative

Source: (Sea Circular, 2020)

The Wangwa Community in Thailand has successfully implemented a circular economy model for plastic waste. The initiative, launched in 2015, significantly reduces landfill waste and increases recycling.

Key Elements
Source Reduction: Focus on reusable items to minimise plastic generation.
Segregation: Careful waste sorting for composting and recycling.
Recycling: The onsite centre turns plastic into new products (pellets, etc.).
Composting: Organic waste enriches soil, reducing reliance on fertilisers.

Outcomes
80% recycling rate, 90% reduction in landfill waste. Job creation and improved quality of life for the community.

4.4 Scenario Four: A Hybrid Framework for a Sustainable Plastics Future

It is 2050, and society stands at a critical point in its journey towards net zero emissions, navigating the complexities of a hybrid economy that equally depends on fossil fuel-derived plastics and bioplastics. This delicate balance highlights a transition phase, symbolizing both advancements toward sustainability and the hurdles that impede the full realization of a circular plastic economy. The juxtaposition of traditional petroleum-based plastics and their bioplastics counterparts illustrates a pragmatic approach to addressing immediate environmental concerns while striving for long-term ecological goals. The petrochemical industry is still invested in new technologies and facilities due to the lock-in effect from its investments during the first quarter of the 21st century, balancing long-term returns on petrochemicals while slowly transitioning to biobased plastics.

4.4.1 Key Features

There is a dual reliance on both types of plastics, each with a solid footing in distinct sectors based on their unique attributes, such as durability, cost-effectiveness and environmental footprint. Technological advancements in recycling have paved the way for more efficient processing capabilities, including sophisticated sorting mechanisms, chemical recycling that breaks plastics down to their molecular components, and specialized biological treatments for bioplastics. Strategic deployment of bioplastics in areas where their environmental benefits are maximized—such as in compostable single-use products—complements traditional plastics in applications that demand longevity. Additionally, integrating Carbon Capture and Utilization (CCU) technologies in producing fossil fuel-derived plastics signifies a concerted effort to mitigate carbon emissions. Regulatory frameworks, including incentives and mandates, support the rationalisation of fossil-derived plastics and the transition towards reduced reliance on fossil fuel-based plastics, encouraging the uptake of bioplastics and incorporating recycled content in new products.

4.4.2 Implications for Climate Change

This hybrid model presents both opportunities and challenges in the context of climate change and the goal of achieving net-zero emissions by 2050. On the one hand, the increased use of bioplastics and the application of CCU technologies contribute to a reduction in the overall carbon footprint of the plastics industry, aligning with broader efforts to mitigate global warming. The innovations in recycling technology augment waste reduction and play a crucial role in reducing reliance on virgin materials, thereby contributing to lower greenhouse gas emissions. On the other hand, the continued use of fossil fuel-derived plastics necessitates a careful balance to ensure that the benefits of CCU and recycling do not inadvertently support a status quo that may lead to lock-in scenarios and delay the transition to more sustainable materials.

4.4.3 Opportunities and Challenges

The opportunities within this hybrid economy are manifold, fostering innovation in recycling, reducing carbon emissions, generating ‘green’ jobs and diversifying the market with environmentally conscious choices. However, the challenges are equally daunting, requiring meticulous resource allocation to prevent adverse environmental impacts, substantial investments in recycling infrastructure to manage the complexity of plastic waste, and sustained efforts in consumer education to promote responsible consumption practices. Navigating these challenges requires a collaborative approach, uniting stakeholders across sectors to foster innovation, implement responsible resource management, and pave the way for a sustainable plastic economy that aligns with the global imperative of carbon neutrality.

Copenhagen's "Minimalist Milk": Sustainable Packaging (Błażejewski et al, 2021)

Problem: Plastic pollution from dairy packaging.

Solution: Reusable glass bottles in supermarkets with a deposit system.

Key Elements
Sleek glass bottles promote reuse.
Circular system: Refilling, sterilisation, recycling.
Transparent carbon footprints inform consumer choice.

Outcomes
70% less plastic waste.
A lower carbon footprint supports climate goals.
Increased consumer awareness and engagement.

Challenges
Scaling infrastructure and shifting consumer habits.
Collaboration and policy for broader adoption.

Lessons
Circular design and reusable packaging are essential.
Partnerships and policy support are key for scaling impact.

5. Chapter Five: The Role of International Collaboration in Plastic Waste Management

5.1 Fostering Global Cooperation on Plastic Waste Reduction

Bilateral and multilateral collaboration can significantly contribute to the transition to a new plastics economy by 2050 (Barrowclough & Birkbeck, 2022). International financial institutions and multilateral development banks (MDBs) are increasingly aligning their investments with Circular Economy (CE) innovations and value chains, embedding these initiatives within broader sustainable development frameworks. This strategic alignment with the Sustainable Development Goals (SDGs) and the Paris Agreement underscores a commitment to financing projects that prioritize recycling, waste minimization, and innovation within the plastics economy. The collaborative pooling of resources among MDBs and donor agencies fosters a low-risk investment climate conducive to further CE engagements(Van Waeyenberge et al., 2020). This collective approach not only facilitates the scaling of impactful initiatives capable of globally transforming the plastics value chain but also enhances the transition's feasibility through economies of scale and shared expertise. Additionally, the emphasis on international circular value chains is pivotal for bolstering domestic remanufacturing and recycling capabilities, thereby diminishing the dependence on new plastic production. Bilateral cooperation -exemplified by the EU Circular Economy Missions to Chile, China, Iran, South Africa, Colombia, Japan, Indonesia and India- is instrumental in developing these value chains, promoting cross-border exchanges of best practices, technologies, and CE innovations (Bellmann, 2021).

Strategic collaborations such as the Memorandum of Understanding on Circular Economy Cooperation between the EU and China and the partnership on sustainable manufacturing (SMEP) between the UK's Department for International Development (DFID) and the UN Conference on Trade and Development (UNCTAD), play a vital role in advancing the CE agenda (Calvin et al., 2021; Luo, 2023). These partnerships are focused on fostering dialogue, sharing best practices, and executing strategies and policies conducive to the transition towards a CE, including within the realm of plastics. By stimulating investments and financing in CE projects, these collaborations are pivotal in driving innovation and research essential for addressing the challenges associated with plastic waste. Moreover, bilateral and multilateral collaborations act as catalysts for innovation, knowledge dissemination and investment in the CE. An integrated approach that marries financial support with policy alignment and technological innovation promises to significantly expedite the shift towards a new, sustainable plastics economy by 2050, ensuring scalability and alignment with overarching environmental objectives (Kedward et al., 2022).

5.2 Sharing Best Practices and Technological Innovations

The transition to a sustainable plastics economy by 2050 is a global imperative that necessitates international collaboration across multiple domains, including the rational use of plastics, enhanced circularity, and the shift towards renewable resources (Calisto Friant et al., 2022). Central to this global endeavour is a commitment to reducing plastic consumption, extending the lifespan of plastic products, and promoting a culture of repair and reuse. Integral to achieving such transformative change is the sharing of best practices and technological innovations among nations. This exchange is crucial for developing a cohesive transnational policy framework, including mechanisms like extended producer responsibility, and for launching worldwide campaigns that elevate public consciousness about responsible plastic usage.

Concrete steps include fostering innovation-friendly regulatory frameworks, promoting circular product design through awareness campaigns and economic incentives, and pooling resources, knowledge, and technologies(Wilson, 2023). This technical cooperation is vital to achieving a planet where plastics contribute to a flourishing circular economy, optimizing resource use and minimizing environmental impact. Through ongoing international research and collaboration, we can effectively evaluate the viability of circular models for plastics, formulate strategies to drive global behavioural shifts towards responsible plastic use and comprehend the broader implications of relying heavily on bioplastic plastics.

5.3 Establishing International Agreements to Regulate Plastics

The escalating plastic pollution crisis necessitates a unified global response, highlighting the critical role of international agreements in regulating plastic use, production, and disposal. These agreements offer a promising avenue for setting universal standards and coordinating efforts to mitigate plastic pollution(Linos & Pegram, 2016). However, the path to establishing such frameworks is fraught with challenges, including divergent national interests, disparities in development levels, enforcement difficulties, the need for comprehensive coverage of the plastic lifecycle, and adapting to new scientific insights. Despite these hurdles, the potential benefits of international cooperation in harmonizing regulations, fostering innovation, facilitating financial and technical support, transforming markets, and enhancing public engagement present compelling opportunities for global action(Ruffini, 2017).

To effectively counter plastic pollution, international agreements must navigate the complex interplay of economic, environmental, and social factors. Harmonizing standards for plastic production and waste management can streamline global efforts, while shared initiatives can accelerate the adoption of sustainable technologies and practices (Rissman et al., 2020). Financial assistance and capacity-building measures are crucial for equipping developing nations to participate fully in these efforts. Moreover, such agreements can drive market shifts towards sustainability, leveraging industry innovation and consumer awareness to foster a circular plastics economy.

Existing frameworks like the Basel and Marpol Conventions, alongside regional initiatives, provide foundational models for international cooperation on plastic pollution (Manyara et al., 2023). These agreements demonstrate the feasibility of collective action but also underscore the need for more comprehensive and adaptable approaches to address the full spectrum of plastic-related challenges. The future of plastics governance requires an overarching governance framework that combines international, national, and local actions, industry engagement, and widespread public participation to ensure a sustainable transition.

Advancing towards a new plastics economy by 2050 demands a concerted effort to refine the architecture of global plastics governance to ensure it is robust enough to drive significant change while remaining flexible to evolving scientific understanding and technological advancements (UNEP, 2022). Critical to this endeavour are considerations of enforcement mechanisms, support for developing nations, prioritization within the plastic lifecycle, and the role of non-governmental actors. Through collaborative international dialogue and innovative policymaking, it is possible to forge a path to a future where plastics contribute positively to a sustainable and circular global economy, ensuring the well-being of the planet and its inhabitants.

5.4 Capacity Building on National Implementation of Global Agreements

Addressing the legacy of plastic pollution and building a sustainable plastics economy requires acknowledging the disparities in starting points and progress across nations (Fletcher et al., 2023). The complexity of achieving carbon neutrality necessitates a nuanced approach that considers local, national, and trade contexts when implementing circular solutions. The transformation unfolds diversely across regions, with some nations facing the challenge of significantly reducing material usage while others strive to stabilize or manage controlled growth. The 2023 Circularity Gap Report sheds light on the varied challenges and contexts different nations encounter in their circular economy journeys (Fraser et al., 2023). The report categorizes nations into three broad profiles: Shift, Grow, and Build.

While recognizing potential overlaps, these profiles amplify key themes characterizing different development trajectories. This framework could be a valuable lens for understanding the unique challenges and opportunities of each nation on the path to circularity.

- Shift Countries: Defined by high living standards and significant resource consumption, high-income nations often overshoot planetary boundaries. Their immediate focus should be on curbing overconsumption and minimizing their environmental footprint.
- Grow Countries: These rapidly industrializing, middle-income nations with expanding middle classes face rising material consumption, sometimes reaching saturation. They must optimise resource use and stabilise consumption levels to maximize societal well-being.
- Build Countries: These countries host most of the global population, using significantly less material than Shift countries. Their focus should be on developing infrastructure and improving well-being in ways that carefully manage any increase in their resource footprint.

Recognizing diverse pathways towards a sustainable plastics economy underscores the need for tailor-made solutions. The shared goal of reversing environmental overshoot and building a thriving circular future requires embracing context-specific approaches.

5.5 Monitoring and Reporting for a new plastics economy

A robust monitoring, evaluation, and indicator framework is fundamental to supporting a sustainable plastics economy (Kumar et al., 2021). Implementing a unified metrics system could significantly enhance stakeholder assessments and decision-making processes, with country baselines playing a pivotal role in tracking progress over time. Technological innovations are key drivers in this transition, necessitating effective monitoring and evaluation systems to measure the progress and impact of advancements in material science, recycling technologies, and infrastructure enhancements for waste collection, sorting, and processing (Mousavi et al., 2023). These systems heavily rely on detailed indicators to assess operational efficiency, environmental footprints, and the scalability of innovative technologies. They are essential for measuring advancements towards material circularity, identifying development or investment requirements, and guiding strategic decisions.

Expanding the range of sustainability metrics is imperative. The planetary boundaries framework provides a comprehensive model for evaluating human activities against Earth-system processes, enabling a balanced assessment of the impact of circular plastic initiatives on critical planetary systems (Richardson et al., 2023; Steffen et al., 2015). This approach facilitates the alignment of strategies with global sustainability objectives. The socio-economic aspects of the transition are equally significant. Evaluating the potential for job creation in new recycling industries affects existing waste sectors, and ensuring the equitable distribution of economic benefits is crucial. Analysing the economic viability of circular models, including cost structures, investment requirements, and market transformation potential, is essential to ensure financial sustainability and accessibility.

In regions where municipal solid waste generation is on the rise, monitoring is increasingly vital for decision-makers (Royle et al., 2022), emphasising the importance of considering social impacts. Social Life Cycle Assessment (SLCA), based on UNEP and the Society of Environmental Toxicology and Chemistry (SETAC) guidelines, offers a framework for analysing the social impacts of products/services. While SLCA primarily employs qualitative analysis, linking these impacts to a functional unit presents challenges. Stakeholders play a critical role in SLCA by identifying social issues. SLCA encompasses numerous potential social impacts, with over 100 indicators listed in the UNEP-SETAC Guidelines, some subject to interpretation.

Extension methods	Abbreviation	Aspect	Indicators
Exergetic life cycle assessment	ELCA	Resource	Cumulative exergy consumption, abatement exergy, environmental sustainability degree.
Life cycle costing	LCC	Economy	Investment costs, operating costs, decommissioning costs, projected revenues and environmental costs.
Social life cycle assessment	SLCA	Society	Social benefits (e.g. local employment), working conditions (e.g. health and safety, fair wages)
The environment–energy–economy model	The 3E model	Sustainability	Integrated environment–energy–economy results.

Table 5. Summary of the extension methods to LCA
Source: (Peng et al., 2022).

Table 5 introduces several LCA extension methods that enhance the traditional LCA framework by incorporating a broader range of considerations into the evaluation of waste management strategies (Peng et al., 2022). The Exergetic Life Cycle Assessment (ELCA) method emphasizes resource efficiency and sustainability, using indicators like cumulative exergy consumption and environmental sustainability degree. Life Cycle Costing (LCC) provides a comprehensive economic analysis, including investment and operating costs, as well as environmental costs, to assess the economic viability of waste management processes. Social Life Cycle Assessment (SLCA) focuses on the societal impacts, highlighting benefits such as local employment and improved working conditions. The Environment-Energy-Economy (3E) Model integrates sustainability by combining environmental, energy, and economic outcomes, offering a holistic view of sustainability. Together, these methods provide a more comprehensive understanding of the impacts of circularity in waste management, ensuring that environmental, economic, and social dimensions are considered in developing sustainable plastic waste management strategies.

Concluding Perspectives: Navigating the Path to Sustainable Plastics by 2050

This report integrates diverse sources to create a panorama of the plastics economy and interventions for mitigating plastic pollution and refining waste management systems with the overarching goal of transitioning towards a carbon-neutral society by 2050. Addressing the ubiquity of marine plastics, as detailed by several sources, requires acknowledging the diverse sources of pollution, including personal care products, rigid plastics, packaging, and synthetic textiles. Concurrently, societal attitudes and behaviours are pivotal in combating this issue, underscoring the necessity for educational and awareness initiatives to shift public perception and foster significant reductions in plastic consumption and pollution.

Innovation in plastic production emerges as a critical solution, with studies indicating the potential of bioplastics and CO_2-derived plastics to reduce the environmental impact of plastic manufacturing. Such advancements align with resource efficiency and energy conservation goals and promote a more sustainable chemical industry. Driving the necessary societal change may require exposing the far-reaching harm caused by microplastics and alternatives to single-use plastics.

Challenges within waste management frameworks, particularly in developing regions, highlight the urgent need for investments in enhanced recycling facilities and innovative waste processing solutions. Transforming waste management infrastructure is a vital step towards our 2050 vision. Developing and implementing more efficient waste sorting, collection, and recycling systems, coupled with policies that incentivize waste reduction and support circular economy principles, is imperative for progress. Moreover, stringent regulations targeting plastic production and waste management, including bans on specific single-use plastics and the introduction of plastic bag levies, have demonstrated efficacy in reducing plastic pollution.

Global collaboration and a unified commitment to minimizing plastic waste and enhancing waste treatment processes are paramount to embed a new plastics economy. Sharing best practices, technologies, and innovations across borders, alongside new concepts such as cradle-to-cradle design, comprehensive impact assessments of plastic products and waste management strategies, will ensure informed decision-making and align collective efforts with long-term sustainability goals. By embracing these strategic interventions, society can transform the vision of a carbon-neutral, plastic pollution-free society by 2050 into a tangible reality, ensuring a healthier planet for future generations.

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