Sadhan Kumar Ghosh
Sannidhya Kumar Ghosh *Editors*

Circular Economy Adoption

Catalysing Decarbonisation Through Policy Instruments

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Preface

Green industrial revolution is the focal point of nations in the globe at present. The nations have been trying to reduce the global extraction rates of natural resources, take climate actions and implement decarbonization in all industrial processes. Researchers, policy makers, NGOs, and governments led by the United Nations have been holding meetings like conference of the parties (COP) about climate change. The countries, who signed the United Nations Framework Convention on Climate Change (UNFCCC)—a treaty agreed in 1994, are planning how to tackle the situation. Green movement for economic success and environmental responsibility go hand in hand.

Environmental calamities—e.g. climate change, extreme weather, loss of biodiversity, extracted ocean and eroded soil—stem from the collision of two systems: Earth’s natural system and humankind’s economic system. In the global perspective, presently we have entered the Anthropocene era, where humans have become the single most influential species on the planet, causing significant global warming and other changes to land, environment, water, organisms, and the atmosphere. All these pushes to a critical juncture of humanity. Scientists have alerted that the current economic model has been pushing the carrying capacity of Earth’s systems to their limits, and that unless the course is changed, the global community will be thrown into unprecedented uncertainty. Tackling the climate requires total systems transformation, from the energy sector to food, cities, production, and consumption. The way our societies and businesses are organized, massive changes are essential to transition to sustainable development. Most of the industrial processes have progressed based on the extract-produce-consume-dispose-deplete (epcd2) concept of the linear economy. The existing systems have experienced tremendous growth while extracting natural resources without limit, leaving the mother earth heavily stressed. We must change and act now immediately to reduce, conserve, and extract natural resources for sustainable development.

Here comes the need of the circular economy (CE) model that offers a new chance of innovation and integration among natural ecosystems, businesses reengineering, our daily lives and society, and waste management. The circular model of resources should be defined in a holistic manner that is internationally accepted. Without urgent action, global waste will increase by 70% on current levels by 2050, according to the World Bank’s report, and the extraction of raw materials is projected to double by 2060 of the 2017 levels. Each activity based on the circular economy concept involved decarbonization with a reduced amount of natural resource extraction resulting in reduced carbon and water footprints. These efforts have also been encouraged and supported by a variety of international and multilateral initiatives, in the framework of the United Nations, the OECD, the European Union, the G7 and G20. Nonetheless, while national, international, and local authorities are progressively scaling up their commitment, further efforts are needed to achieve a more resource-efficient, decarbonization and circular economy.

Considering the importance of the circular economy, a research project entitled "circular economy adoption and decarbonization" was established in which experts from 50 countries have been participating from November 2022 to continue till December 2030. The project was launched in the meeting of the International Scientific Committee at the International Conference on Sustainable Waste Management & Circular Economy platform in November 2017 at Hyderabad during the seventh IconSWM by International Society of Waste Management, Air and Water (ISWMAW) in India by a group of scientists, policy makers, practitioners, and NGOs from 21 countries. The outcome of the project is documented in the books, *Circular Economy: Global Perspective* in 2019 and *Circular Economy: Recent Trends in Global Perspective* in 2022 of this Circular Economy Initiative (CEI) of the International Society of Waste Management, Air and Water which are contributed by seventy experts from 21 countries published by Springer Nature. This book consists of 14 chapters in four parts contributed by 42 researchers from 14 countries—Australia, Canada, China, Germany, Hungary, India, Indonesia, Italy, Japan, Kenya, Mexico, Turkey, UK, USA, and UNIDO representative.

Part I: Decarbonisation and Policies for Circular Economy Adoption
• Circular Economy Catalysing Decarbonisation
Part II: Policy Supports Towards Circular Economy
• Policies & Practice of Sound Material Cycle Society in Japan: Transition Towards CE
• Pathway Towards CE Development in China: Policies, Case Studies & Role of Universities
• Circular Economy Policies and Innovations in Africa
• Waste Management in Indonesia: Strategies and Implementation of SDGs and CE
Part III: Implementation Status of Circular Economy Concepts
• On the Way to Circular Economy: Türkiye's Waste Management and Zero Waste Project
• Circular Economy Transition in Italy in Key Priority Sectors
• Status of the Adoption and Practice of Circular Economy in Mexico
Part IV: Circular Economy Adoption in Industries
• Circular Manufacturing Transformation: Manufacturing Perspectives, CE Implementation in Asia
• The Circular Economy, Employment and Low Carbon in the UK Manufacturing Sector
• Circular Economy Through Technology for Waste-to-Energy
• Utilization of Household Sewage Sludge: Effect of the Pyrolysis Temperature on Chemical Properties
• Shifting Toward Resource Management in Remote Area: Case Study of Lake Toba, Indonesia
• Circular Bioeconomy Through Anaerobic Digestion

The book presents an overview of the co-relationship between circular economy and decarbonization, policies and strategies in China, Japan, Indonesia, and Kenya, the transition of CE adoption in Turkey, Mexico, and Italy, and last six chapters present the adoption of Circular Economy and decarbonization projects in industrial processes, namely, manufacturing sectors, waste-to-energy sectors using different feedstock materials including sewage sludge, and resource efficiency in villages in Indonesia. The collection is comprehensive in its coverage of various issues, focusing on the transitional requirements for countries. This book will definitely make a significant difference to the understanding of readers about the circular economy, decarbonization, and implementation strategies.

The authors gratefully acknowledge the support of the contributors, reviewers, committee members of ISWMAW, the editorial board members of the *Journal of Solid Waste Technology and Management* (JSWTM), and their PhD & PG research scholars. The authors must acknowledge the support and encouragement extended by Mrs. Pranati Ghosh and Mrs. Prativa Ghosh. Special thanks are expressed by the authors to the editors and the staff members at Springer Nature, namely, Mr Aninda Bose, Ms. Aakanksha Tyagi, Mr. Ashok Kumar, Ms. Shruthi Radhakrishnan, Ms. Rhea Dadra, and Ms. Mahalakshmi Shankar. The authors recognize the contribution of those who are working for innovation and implementation of Circular Economy concepts worldwide which in one way or the other adds value to the book.

The target audience of the book is researchers, policy makers, municipal administration, industries, NGOs, and students who work on resource efficiency, circular economy, waste management, policy making, environment management and engineering, and in allied areas of academic fields. The book will also be helpful for the implementers of Circular Economy and 3R concepts. The book will be a treasure for libraries and online repositories.

We are hopeful that the book will be helpful to the readers who are welcome to provide any feedback.

Kolkata, West Bengal, India — Sadhan Kumar Ghosh
Denver, CO, USA — Sannidhya Kumar Ghosh
2023

Contents

Editors and Contributors

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Sannidhya Kumar Ghosh PhD (USA), serves as Structural Engineer at DCI Engineers Ltd, Denver. He graduated in civil engineering from Jadavpur University. He did his MS and PhD from the Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder (UCB), USA. He served as the instructor and postdoc at UCB. His research areas include circular economy, concrete and building design in high seismic region, earthquake characteristics, impact of materials ageing during earthquake, structural dynamics, C&D waste management, etc. He carried out projects at Aston University, and Loughborough University UK under UKIERI Scheme funded by British Council and at IIT, Kanpur, under TEQIP funding respectively. He has a few publications and books. He is the governing council member of International Society of Waste Management, Air and Water (ISWMAW).

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Part I

Decarbonisation and Policies for Circular Economy Adoption

Circular Economy Catalysing Decarbonization

1

Sadhan Kumar Ghosh and Sannidhya Kumar Ghosh

Abstract

Experts, scholars, and policy makers worldwide have proved and accepted that global warming is real with scientific evidence. The Paris Agreement sets the goals of keeping global warming to well below 2 °C and as close to 1.5 °C as possible compared to pre-industrial levels. On the other hand, the extraction rates of natural resources are increasing at a higher rate. Actions are very much required to control all these issues. Circular economy thinking is a recognition that we can no longer be indifferent to the finite resources of the globe. New business models and tools have been developed that will support a more resilient future. Circular economy will help reducing the extraction of natural resources with its regenerative concepts. Decarbonization can refer to moving away from energy systems that produce carbon dioxide (CO_2) and other greenhouse gas emissions or it can refer to removing carbon build up and carbon deposits from internal combustion engines. Both the processes have the same objectives of removing carbon, but in different ways. Energy decarbonization involves shifting the entire energy system to stop carbon emissions from entering the atmosphere before they are ever released and part of that process also involves using carbon capture technologies to remove CO_2 from the air after it has already been released. This involves decarbonizing power grids, decarbonizing supply chains, and utilizing carbon sequestration in the pursuit of net-zero emissions and a carbon neutral global economy. Circular economy will help making longer life

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cycle of products, conserve resources leading to zero wastage and help decarbonization by reducing carbon footprints. The sustainable development goals encourage the implementation of circular economy and decarbonization with an integrated approach by all stakeholders in the society. This article studies how the circular economy catalyse the decarbonization.

1.1 Introduction

We are in the middle of a climate crisis. The climate crisis is featured every day in the media reporting the images of floods, melting of ice, droughts, forest fires, and the damage these disasters inflict on local populations, particularly the downtrodden people in the society. The 2020 was set to kick-start the "decade of action" for the UN Sustainable Development Goals ("Sustainable Development Goals", https://www.un.org/sustainabledevelopment/decade-of-action/). To date, thousands of experts and scholars worldwide have proved that global warming is real with all kinds of scientific evidence (Fawzy et al. 2020). The Paris Agreement sets the goals of keeping global warming to well below 2 °C and as close to 1.5 °C as possible compared to pre-industrial levels, making all economies resilient to climate impacts, and ensuring that financial flows are consistent with these objectives (UNFCCC 2015). The task is enormous: the transformations needed will require realigning 7–19% of GDP worth of private and public spending every year. The 2020 Circularity Gap Report recorded a bleak, first-time milestone of 100 billion tons of materials enters the global economy every year. These materials are funnelled through our economy and allow us to continue our way of life. However, of this massive amount, only 8.6% is recycled and returned to the economy reducing the extraction of natural resource. The towns and cities are a major source of the greenhouse gas emissions (GHGs) that aggravate the climate crisis. The report entitled, "Circular Cities Impacts on Decarbonization and Beyond" in its January 2022 edition commented that, "with global projections indicating that there will be another two billion on the planet by the time we reach the 2050 target for Net Zero, it is clear that we need to tackle the GHGs in the built environment if we want to have any chance of mitigating the worst of the climate impacts to come". The same is also true to India, where the highest population of 1.42 billion in the globe resides as in April 2023. To reach its temperature goals, the Paris Agreement and the subsequent decisions of its parties give central importance to emission reduction strategies, decided by and for individual countries, following the principle of common but differentiated responsibilities and respective capabilities. This can take the form of Nationally Determined Contributions (NDCs) or Long-term Low-emission Development Strategies (known as LEDS, LT-LEDS or LTS). More than 50 countries globally, including 11 in Latin America and the Caribbean—have enacted targets to reach net-zero carbon or greenhouse gas (GHG) emissions, and more than 140 other countries have announced or are considering similar targets (Net Zero Tracker 2022; Andreas et al. 2022).

Circular economy concept is a recognition that we have to concern about the finite resources of the globe. New business models and tools have been developed that will support a more resilient future. It has been studied and observed by several researcher that circular thinking is already driving practical change, showcasing some of the success stories that demonstrate that significant difference can be made access to the right tools and a willingness are demonstrated to take action.

In last centuries, the global consumption and resource use can be described as "epcd2" (extract-produce-consume-dispose-deplete), or, "take-make-use", a linear economy approach (Ghosh et al. 2022). There are no questions about the growth that took place during last centuries with the *epcd2* approach but with the rates of increase in global extraction of natural resources, the scientists, environmentalists, and the policy makers were worried about the sustainability. Moreover, the processes following epcd2 involved huge over-consumption to the detriment of planetary health. The evolution of the concept and practice of the new circular economy models opens up the eyes of the global community and encourage to have the focus from "epcd2" with a paradigm shift to "zero-waste" and resource conservation focus of circular economy. Instead of depleting the resources at the end-of-life time of the intended use of a product. It is considered as a secondary raw material for a second production process. A circular economy is restorative and regenerative by design and aims to eliminate the concept of waste as per Ellen MacArthur Foundation. The "epcd2" process involves more carbon footprints than that of the processes following "Zero-Waste" model of circular economy as per Ghosh et al. (2022). This way the circular economy contributes to the extraction of natural resources and decarbonization in the processes. These characteristics present new ways to reduce consumption-based emissions while creating added value in terms of resilience and quality of life.

Seven core societal needs, namely, Housing, Nutrition, Mobility, Communications, Services, Consumables, and Healthcare have been identified in The Circularity Gap Report 2021 which have a big potential to cut down attributed emissions and resource use once circular economy concepts are implemented. A consensus has been reached that the surge in human-caused carbon emissions is the primary cause of global warming. The concept of carbon neutrality is designed to control global temperature rise (Chen 2021). Three key human needs, housing, mobility, and nutrition, are responsible for almost 70% of global emissions. Only 8.6% of the whole economy is circular which needs to be almost double to 17% to keep the planet sustainable. Circular strategies can "drastically reduce" the amount of minerals, fossil fuels, metals, and biomass consumed by the world's economy. Climate change and environmental restoration are top priority for the nations and local governments around the world. Cities account for 70% of global carbon emissions, 60% of resource use, and produce 50% of global waste and in this context, they are a part of the problem (Enel 2022).

COP27 is another crucial milestone to a net-zero world. In last few years companies were focusing on addressing direct emissions from company-owned and controlled resources from activities at the firm level, as well as emissions related to the generation of purchased energy, steam, heat, and cooling. The more we know about how the supply chains work, the more focused approaches can be adopted to close loops and concentrate on resilience. The planetary temperature continues to rise due to the heat-trapping nature of the greenhouse gas (GHG) emissions, more people and infrastructure are at risk, costing our economy heavily. Hence, it becomes necessary to adopt practices to reduce or zero down the carbonization from the firm level activities. To discuss about the decarbonization, it is pertinent to discuss about the Carbon Footprints. The next section will elaborate on Carbon Footprint and greenhouse gases.

1.2 Carbon Footprints and Greenhouse Gases

Carbon footprint has become a widely used term and concept in the public debate on responsibility and abatement action against the threat of global climate change and an essential concept for assessing the impact of human activities on the ecological environment (Wiedmann and Minx 2008a, b). It is mainly used to measure GHG emissions (Hammond 2007). While the term itself is rooted in the language of Ecological Foot printing (Wackernagel and Rees 1996), the common baseline is that the carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with production or consumption activities.

Nowadays, the carbon footprint has become combining the concept of carbon footprint with other energy research objects to study the effect of Carbon emission (CE_m) on the ecological environment from different perspectives, such as fossil energy footprint (Wiedmann and Minx 2008a, b), nuclear energy footprint (Stoeglehner and Narodoslawsky 2009), clean energy footprint (Chen and Lin 2008), wind energy footprint (Santhanam 2011), and solar energy footprint (Brown 2009). The popular method for determining the carbon footprint involves calculating the CE amount from energy utilization or converting CE amount into an equivalent bioproductive land area (Galli et al. 2012; Bonfiglio et al. 2020)

Several researchers have developed the definition of Carbon Footprints (CF) for better understanding. As per the dictionary, carbon footprints (plural noun) are the amount of carbon dioxide released into the atmosphere as a result of the activities of a particular individual, organization, or community. Carbon footprint is defined as the measure of the total greenhouse gas emissions released into the atmosphere. These emissions are caused by the choices and actions of an individual, company or a nation. Carbon footprint is measured in terms of carbon dioxide emissions (CO_2). In other words, Carbon footprint is the amount of carbon dioxide (CO_2) emissions associated with all the activities of a person or other entity (e.g., building, corporation, country, etc.). It includes direct emissions, such as those that result from fossil fuel combustion in manufacturing, heating, and transportation, as well as emissions required to produce the electricity associated with goods and services consumed. In addition, the carbon footprint concept also often includes the emissions of other greenhouse gases, such as methane, nitrous oxide, or chlorofluorocarbons (CFCs) (Selin 2023a, b). Table 1.1 demonstrates a few definitions of Carbon Footprints proposed by different researchers and organizations. Most researchers and organizations in defining CF dealt with the question of how much carbon dioxide emissions can be attributed to a certain product, company or organization, although none of them provides unambiguous definition of the term carbon footprint. In the definitions it has been observed that "carbon footprint" is used as a generic synonym for emissions of carbon dioxide or greenhouse gases expressed in CO_2 equivalents.

ISO 14067: 2018 has also defined as the partial carbon footprint of a product as the sum of GHG emissions and GHG removals of one or more selected process (es) in a product system, expressed as CO_2 equivalents and based on the selected stages or processes within the life cycle. A partial CFP is based on or compiled from data related to (a) specific process(es) or footprint information modules, which is (are) part of a product system and can form the basis for quantification of a CFP. More detailed information on information modules is given in ISO 14025:2006, 5.4. "Footprint information modules" is defined in ISO 14026:2017, 3.1.4. The results of the quantification of the partial CFP are documented in the CFP study report expressed in mass of CO2e per declared unit.

As per ISO 14067: 2018, carbon dioxide (CO_2) equivalent, CO_2e is the unit for comparing the radiative forcing of a GHG to that of carbon dioxide. Mass of a GHG is converted into CO_2 equivalents by multiplying the mass of the GHG by the corresponding GWP (Global Warming Potential) or GTP (Global Temperature Potential) of that gas. In the case of GTP, CO_2 equivalent is the unit for comparing the change in global mean surface temperature caused by a GHG to the temperature change caused by CO_2 (Source: ISO 14064-1:2006).

It is essential to understand greenhouse gases (GHGs) while discussing carbon footprint. GHGs are responsible for keeping our planet warm. Without them, the earth would be uninhabitable. Water vapour, methane from natural gas, nitrous oxide from soils and oceans, ozone, and carbon dioxide are its main constituents. Greenhouse gases protect us from the sun's radiation and regulate the internal heat on the planet. But a significant increase in greenhouse gases also represents a risk. Greenhouse gases (GHGs) act like a blanket insulating the Earth and warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space; Different GHGs can have different effects on the Earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radiative efficiency"), and how long they stay in the atmosphere (also known as their "lifetime").

1.2.1 GWP (Global Warming Potential) and GTP (Global Temperature Potential)

While discussing the carbon footprints and greenhouse gases (GHGs), two terminologies—Global Warming Potential (GWP) and Global Temperature

Table 1.1 Definition of carbon footprints

Definition	Reference
Carbon footprint of product is the "sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change"; A CFP can be disaggregated into a set of figures identifying specific GHG emissions and removals. A CFP can also be disaggregated into the stages of the life cycle. The results of the quantification of the CFP are documented in the CFP study report expressed in mass of CO_2e per functional unit	ISO 14067: 2018 Greenhouse gases—carbon footprint of products-Requirements and guidelines for quantification
The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product	Wiedmann and Minx (2008a, b)
"The carbon footprint is the amount of carbon dioxide emitted due to your daily activities—from washing a load of laundry to driving a carload of kids to school"	
The carbon footprint was calculated by "measuring the CO_2 equivalent emissions from its premises, company-owned vehicles, business travel and waste to landfill"	British Sky Broadcasting (Sky)
". . . a methodology to estimate the total emission of greenhouse gases (GHG) in carbon equivalents from a product across its life cycle from the production of raw material used in its manufacture, to disposal of the finished product (excluding in-use emissions)". ". . . a technique for identifying and measuring the individual greenhouse gas emissions from each activity within a supply chain process step and the framework for attributing these to each output product (The Carbon Trust will refer to this as the product's 'carbon footprint')"	
". . . the full extent of direct and indirect CO_2 emissions caused by your business activities"	Schneider Electric (2021)
". . .the 'Carbon Footprint' is a measure of the impact human activities have on the environment in terms of the amount of greenhouse gases produced, measured in tonnes of carbon dioxide"	
"The demand on biocapacity required to sequester (through photosynthesis) the carbon dioxide (CO_2) emissions from fossil fuel combustion"	Global Footprint Network (2007)
"A carbon footprint is a measure of the amount of carbon dioxide emitted through the combustion of fossil fuels. In the case of a business organization, it is the amount of CO_2 emitted either directly or indirectly as a result of its everyday operations. It also might reflect the fossil energy represented in a product or commodity reaching market"	Grubb and Ellis (2007)
"A 'carbon footprint' is the total amount of CO_2 and other greenhouse gases, emitted over the full life cycle of a process or product. It is expressed as grammes of CO_2 equivalent per kilowatt hour of generation (gCO_2eq/kWh), which accounts for the different global warming effects of other greenhouse gases"	Parliamentary Office of Science and Technology

Potential (GTP) must be discussed for easy understanding. Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers and scientists to compare emissions reduction opportunities across sectors and gases.

An alternate metric of GWP is the Global Temperature Potential (GTP). The GTP is a measure of the temperature change at the end of that time period relative to CO_2, whereas GWP measures the heat absorbed over a given time period due to emissions of a gas. The calculation of the GTP is more complicated than that for the GWP, as it requires the modelling for how much the climate system responds to increased concentrations of GHGs (the climate sensitivity) and how quickly the system responds (based in part on how the ocean absorbs heat) (USEPA 2023). Table 1.2 demonstrates the GHG components, their estimated GWP, their estimated lifetime, and other related information.

The Carbon Emission (CE_m) of power generation mainly refers to the Carbon Emission of coal, oil, natural gas, and other fossil fuel combustion in the process of thermal power production. In addition to the direct CE_m of production process, the CE_m of power generation also includes the implicit CE_m (Stoeglehner and Narodoslawsky 2009; Zhang et al. 2017). In decarbonising certain industry segments and long-distance transport, hydrogen could play a significant role in European Union. The associated technologies are largely at an early stage of deployment and are not very competitive with fossil fuel alternatives. This may be noted that the hydrogen consumed today is mostly derived from fossil fuels. In particular, the European Union and its Member States have recently reasserted their intention to implement Contracts for Difference (CfDs) to support hydrogen production (Bouacida 2023). Some hydrogen technologies are key to the decarbonization of industry, including electrolysis for hydrogen production and the direct reduction of iron ore with hydrogen for steel production (Bouacida and Berghmans 2022; IEA 2019; Ueckerdt et al. 2021). Currently, although alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis are fairly mature technologies, they remain sparsely deployed; while other electrolysis technologies, such as solid oxide electrolysis (SOEC), are still not at the commercial stage but could significantly contribute to decarbonization (IEA 2023).

In 2019, the transport sector accounted for 23% of total CO_2 emissions from energy and industrial processes, with passenger cars at 9%, or just over 3 $GtCO_2$ (IEA NZ 2021). The passenger car emissions need to decrease by 11% per year for the next 30 years according to the IEA's Net Zero Emission (NZE) scenario by 2050. Only 16% of the NDCs submitted by October 2021 by different nations included transport emission reduction targets, with the vast majority of measures discussed focusing only on reducing fuel consumption, developing low-carbon fuels, and electric vehicles (OECD/ITF 2021). NDCs also need to be developed in conjunction

Table 1.2 GHG components, estimated GWP, and lifetime

The GHG components	Estimated GWP	Lifetime	Remarks
Carbon dioxide (CO_2)	GWP of 1 regardless of the time period used, because it is the gas being used as the reference	CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years	
Methane (CH_4)	GWP of 27–30 over 100 years	CH_4 emitted today lasts about a decade on average, much less time than CO_2. CH_4 absorbs much more energy than CO_2	Net effect of shorter lifetime and high energy absorption is reflected in GWP. CH_4 GWP accounts for some indirect effects, e.g., CH_4 is a precursor to ozone, which itself is a GHG
Nitrous oxide (N_2O)	GWP 273 times that of CO_2 for a 100-year timescale	N_2O emitted today remains for more than 100 years, on average, in the atmosphere	
Chlorofluorocarbons (CFCs)	Called high-GWP gases	For a given amount of mass, CFCs trap substantially more heat than CO_2	GWPs can be in the thousands or tens of thousands
Hydrofluorocarbons (HFCs)	Called high-GWP gases	For a given amount of mass, HFCs trap substantially more heat than CO_2	GWPs can be in the thousands or tens of thousands
Hydrochlorofluorocarbons (HCFCs)	Called high-GWP gases	For a given amount of mass, HCFCs trap substantially more heat than CO_2	GWPs can be in the thousands or tens of thousands
Perfluorocarbons (PFCs),	Called high-GWP gases	For a given amount of mass, PFCs trap substantially more heat than CO_2	GWPs can be in the thousands or tens of thousands
Sulphur hexafluoride (SF_6)	Called high-GWP gases	For a given amount of mass, SF_6 traps substantially more heat than CO_2	GWPs can be in the thousands or tens of thousands

with long-term low GHG emission development strategies, to achieve the ambition level to commensurate with what is needed to reach net-zero in 2050 (Waisman et al. 2019). Currently, 50 countries have submitted such long-term strategies (UNFCCC 2022), providing coverage for more than 40% of global CO_2 emissions (IEA NZ 2021), and only ten countries mentioned a 2050 transport targets (SLOCAT 2021).

Transport sector is one of the significant sectors that has higher carbon footprints. In Brazil, India, Indonesia, and South Africa, passenger transport emissions accounted for 4–7% of national GHG emissions in their baseline years (2019 in Brazil, 2012 in India, 2010 in Indonesia, and 2017 in South Africa). However, while the population and access to mobility continues to grow in all countries, analyses highlight possible pathways for a low-carbon transition of the passenger transport sector. Passenger transport emissions could be reduced by 35–90% between 2050 and the baseline years 2012 and 2017 in India and South Africa, respectively, reaching less than 0.04 tCO_2eq/capita, around 0.1 tCO_2eq/capita in Indonesia and around 0.2 tCO_2eq/cap in Brazil (Yann et al. 2023). On a per passenger kilometres travelled (pkm) basis, emissions are reduced by 66–92% in 2050 relative to the baseline years, reaching less than 8 gCO_2eq/pkm in India and South Africa and around 12gCO_2eq/pkm in Indonesia and Brazil. It should be noted that the average passenger domestic transport emissions per capita in non-OECD countries lies around 0.5 tCO_2/cap, while OECD countries have values of around 3 tCO_2/cap (OECD/ITF 2021). The share of passenger mobility by cars or motorized two-wheelers seen today varies considerably between countries (Fig. 1.1).

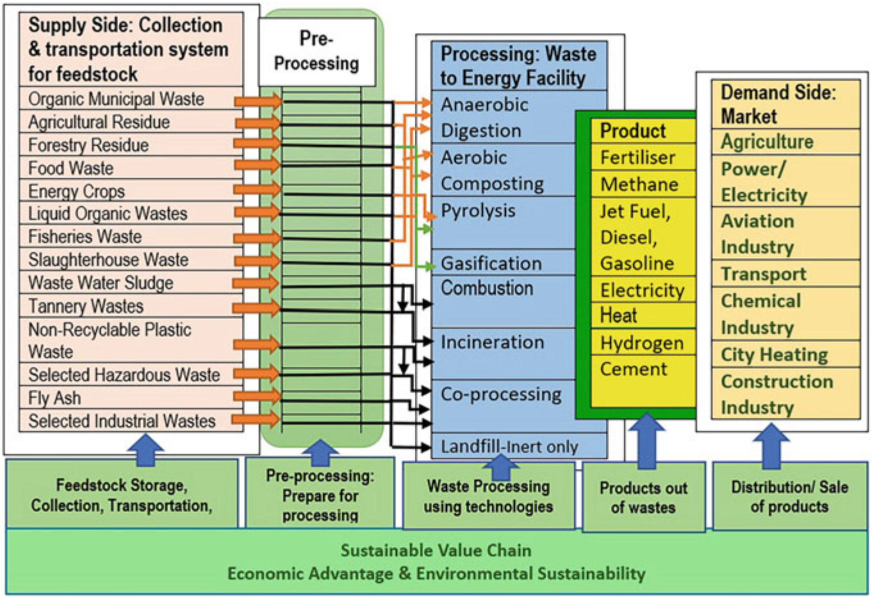

Fig. 1.1 Share of private motorized mobility (car and motorized 2-wheelers) in total mobility (% Gpkm), 2020–2050 (Source: Adopted from Yann et al. 2023)

In the figure, it is observed from the data in combination these represents more than 53% of passenger mobility in Indonesia representing a larger share of motorized 2-wheelers (35%) and a lack of public transport. While it accounts for less than 30% in India, public transport is highly subsidized by the government to support the lower- and middle-class population (70% of the total population), who therefore travel more by public transport. The objective of the nations is to allow people with more incentives continue preferring public transport.

1.3 Direct and Indirect Carbon Emissions Accounting

Carbon accounting, also known as a carbon or greenhouse gas inventory, is the process of measuring the amount of carbon dioxide, or other greenhouse gas (GHG), an organization emits help the entity in understanding its climatic impact. Carbon accounting is very important in the business today. The process helps organizations highlight and target high GHG emitting operations with emission reduction strategies. As such, in 2022, 81% of S&P 500 companies reported their own emissions (scope 1), and the emissions of the electricity they bought (scope 2). In addition, globally, over 22,000 companies disclosed environmental data with a focus on business emissions to the Carbon Disclosure Project (CDP) in 2022. The business houses need to understand sources of emissions are coming from and the volume exuded, to then devise and implement an effective GHG reduction program.

The first meeting of the Conference of the Parties (COP1) held in 1995 in Berlin, which launched strict and precise commitments to mitigate climate change in the name of, “Kyoto Protocol” while COP28 to the UNFCCC is scheduled during November–December 2023 in the United Arab Emirates. The protocol sets binding and measurable objectives for combating climate change for the first time, stipulating global ceilings for GHGs. COP21 took place in Paris in 2015, and marked a new momentum for climate action duly signed the Paris Agreement on Earth Day (April 22, 2016), at the UN headquarters in New York by 192 states and the EU—representing 98% of global GHG emissions. It outlined the action necessary to limit global temperature rise this century below 35.6 °F (2 °C) (which is warmer than pre-industrial levels), and to cap further temperature increases to 34.7 °F (1.5 °C).

However, scope 1, scope 2, and scope 3 for Carbon accounting and reporting need to be understood. The Greenhouse Gas (GHG) emission accounting is divided into three scopes while calculating (https://greenbusinessbureau.com/green-practices/energy/what-is-carbon-accounting/). Carbon footprint is categorised under three scopes:

1.3.1 Scope 1 Emissions

Scope 1 or Direct Emissions, as defined by the GHG Protocol, are GHGs released directly by the business in question by the burning of fossil fuels onsite. Personal vehicles and gas stoves are examples of scope 1 emissions. For simplicity, when defining scope 1 emissions, think “*burnt*”. Emissions from chemical production in owned or controlled process equipment falls under scope 1. Direct CO_2 emissions from the combustion of biomass shall not be included in scope 1 but reported separately. GHG emissions not covered by the Kyoto Protocol, e.g., CFCs, NOx, etc. shall not be included in scope 1 but may be reported separately.

1.3.2 Scope 2 Emissions

Scope 2 or Indirect Emissions, as defined by the GHG Protocol, are indirect GHGs released due to the energy purchased by the business in question. Energy purchased are referred to the electrical energy (purchased or acquired electricity, steam, heat, and cooling, called "scope 2 emissions"). Companies that emit carbon, but purchase electricity are examples of scope 2 emissions. For simplicity, when defining scope 2 emissions, think "*bought*". Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where electricity is generated. These emissions physically occur at the facility where electricity, steam, and cooling or heating are generated. But as a user of the energy, the consuming party is still responsible for the Greenhouse Gas Emissions that are being created.

1.3.3 Scope 3 Emissions

Scope 3 or Other Indirect Emissions, as defined by the GHG Protocol, are indirect GHGs released across an organization's value chain. For simplicity, when defining scope 3 emissions, think "*beyond*". All indirect emissions which are the result of a companies' activities fall under Scope 3 emissions, such as the production of goods, transportation of purchased fuel, and at an individual scale; using those produced goods. Scope 3 is an optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services.

In very simple understanding,

Scope 1: Emission from Gas and company car fuel used.

Scope 2: Emission from purchased Electricity Consumed by the company

Scope 3: Everything else. Split in to 15 sub-categories. Emission from other than scope 1 and 2.

Scope 1 is direct while scope 2 and scope 3 are indirect. Scope 3 includes the carbon emission takes place in any of the activities which are purchased by the company but not the own activities. Carbon footprints for the company in scope 3 is 80–90% of the total carbon footprints of the company. The GHG Protocol outlines 15 categories that fall under scope 3 emissions (Fig. 1.2). These categories are grouped as either upstream or downstream activities (Greenhouse Gas Protocol 2011). The overview of scope 1, 2, and 3 and possible associated activities in the value chain of a company as per the GHG protocol are demonstrated in Fig. 1.3 and

Fig. 1.2 Scope 3 emissions—15 categories as per GHG Protocol outlines

Fig. 1.3 Overview of GHG protocol, Scope 1, 2, and 3 and emission in value chain (partially adopted from Greenhouse Gas Protocol 2011 developed by authors)

Table 1.3. Scope 1, scope 2, and scope 3 are mutually exclusive for the reporting company, such that there is no double counting of emissions between the scopes.

1.3.4 Carbon Neutrality and Net-Zero Goals

The global carbon neutrality goal requires countries to go beyond incremental transformations, often resulting from past trends, to consider systemic transformations with "rapid and far-reaching transitions in energy, land, urban, and

Table 1.3 Overview of the scopes (Adopted from Greenhouse Gas Protocol 2011)

Types of emission	Scope	Specification	Examples of activities/entity
Direct emissions	Scope 1	Emissions from operations that are owned or controlled by the reporting company; these sources are owned or controlled by the reporting company	Emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment
Indirect emissions	Scope 2	Emissions from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company. The sources are owned or controlled by the reporting company	Use of purchased electricity, steam, heating, or cooling
Indirect emissions	Scope 3	All indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions, which are the consequence of activities of the reporting company, occur at sources owned or controlled by another company	Production of purchased products, transportation of purchased products, or use of sold products

infrastructure (including transport and buildings), and industrial systems" (IPCC 2018a, b). Despite the momentum of decarbonization, organizations are still found slow to act on climate change and decarbonization. As of early 2020, only 23% of the Fortune 500 had set meaningful commitments to carbon neutrality, climate action, or both. Progress in European head quartered Fortune Global 500 companies has been slightly more promising, with 42% taking action or publicly committed. Several theories and postulates are being evolved and proposed by researchers and policy makers for decarbonization. The report "Achieving Net-Zero Prosperity. . .. . . (2022)" demystifies what financing the transition to net-zero emissions means. It gives a guideline for the transition towards carbon-free prosperity. Fifteen transformations (Table 1.4) in different areas have identified that rely on existing technology can help deliver deep emission reductions, acting on electricity; transport; agriculture, forestry and land use; buildings; industry; and waste management (Andreas et al. 2022). It is necessary to understand the difference between carbon neutral vs. net-zero goals. Often carbon neutral and net-zero goals are used interchangeably, the terms *carbon neutral* and *net-zero* actually represent very different approach to decarbonization and combatting climate change.

Carbon Neutrality was first proposed in 1997 by the UK's Future Forests as a business planning concept that focuses on pathways to Carbon Neutrality from an energy technology perspective in areas of transport, tourism, family life and personal behaviour. It offsets carbon emissions by buying certified carbon credits. The British

Table 1.4 Fifteen potential transformations that can help deliver deep emission reductions

Major transformations area	Transformation serial numbers	Description of transformation
Electricity	Transformation 1	Accelerate carbon-free variable and flexible electricity generation through sources such as solar, wind, geothermal, and hydropower
	Transformation 2	Phasing out all fossil fuel electricity generation, such as coal, natural gas, and diesel
Transport	Transformation 3	Reduce individual motorized transport and increase public transport, walking, and biking
	Transformation 4	Replace diesel and gasoline passenger vehicles with electric and zero emission vehicles
	Transformation 5	Shift freight transport to rail, water and low- or zero emission technologies
Agriculture, forestry and land use	Transformation 6	Modernize farming practices to reduce emissions of methane and nitrous oxide
	Transformation 7	Pursue conservation of forests and other high-carbon ecosystems and farmland restoration
	Transformation 8	Reduce consumption of beef and dairy
Buildings	Transformation 9	Achieve the highest possible energy efficiency for building shells and appliances
	Transformation 10	Electrify building appliances
	Transformation 11	Deploy solar electricity and hot water generation on buildings
Industry	Transformation 12	Electrify low heat industry
	Transformation 13	Replace all fuels and feedstocks in heavy, high-heat industry with lower-emissions alternatives
Waste	Transformation 14	Work towards a circular economy
	Transformation 15	Reduce food loss and waste and implement active methane management for organic material disposal

Standards Institute (BSI) defines carbon neutrality as a phenomenon in which a product (or service) does not cause a net increase in greenhouse gas emissions to the atmosphere over its life cycle. Carbon neutrality is a voluntary behaviour that emphasizes the transformation of economic structure and energy structure. Moreover, it includes the need to accelerate innovative application of low-carbon and zero-carbon technologies, focusing on energy conservation and energy efficiency. Carbon neutrality emphasizes on accelerating the application of renewable energy, expanding the construction of forests and carbon sinks, and promoting the balance between greenhouse gas emissions and absorption of the earth. The transportation sector accounts for nearly 60%of oil consumption. Under the background of carbon neutrality, the exploration and practice of traditional fossil energy transformation in the field of transportation has become an important part of green transportation.

In 2019, the UK government became the first major economy to pass a net zero emissions law. With it, a target that will require the UK to bring all greenhouse gas emissions to net zero by 2050. Net zero means that any carbon emissions created are balanced (kind of cancelled out) by taking the same amount out of the atmosphere. Therefore, net zero can be reached when the amount of carbon emissions we add is no more than the amount taken away. There are many ways to remove carbon from the atmosphere, for example, you can plant trees which absorb CO_2 and release oxygen. When carbon (CO_2 or carbon dioxide) and other heat-trapping emissions are released into the air, they act like a blanket, holding heat in our atmosphere and warming the planet. Traditional energy sources such as coal and gas produce carbon dioxide among other gasses when they are burned to fuel power stations. Zero carbon means that no carbon emissions are being produced from a product or service (for example, a wind farm generating electricity, or a battery deploying electricity). Energy sources like wind, nuclear and solar do not create carbon emissions when they are used to produce electricity—we refer to these sources as zero-carbon (NGESO 2022).

Net zero is all about "balancing" or cancelling out any carbon we produce. We reach net zero when the amount of GHG we produce is no more than the amount taken away. Zero carbon concerns the emissions produced from a product or service—it means no carbon is given off at all. In the context of energy generation, one example would be a wind turbine creating electricity which does not give off any carbon.

1.3.5 Carbon Offsets and Carbon Credits

The overall goal of the carbon mechanisms, carbon offsets and carbon credits are to reduce emissions, and to remove the greenhouse gases that have already been emitted to the atmosphere. When a company reduces its GHG emissions, it can earn carbon credits which may then be traded to other companies which need to offset their own emissions. A carbon credit gives the purchaser permission to emit a specified amount of carbon, because another entity has emitted less carbon pollution and effectively has a credit that they can sell. A carbon credit represents the right to emit one metric ton of carbon dioxide. These credits are used by companies, industries, and governments. The majority of carbon credits are bought and sold through cap-and-trade systems between different companies and brokers. The goal of carbon credits is to make emitting carbon more expensive, incentivizing companies to work towards emitting less on their own.

Carbon Offsetting: The practical process that give rise to a carbon credit. Carbon Offsetting involves a project - such as a renewable energy project or a tree planting event- that removes atmospheric GHG emission.

Carbon Credits: A tangible measure illustrates how much CO_2 or other GHG has been removed from the atmosphere via a given Carbon Offset project – with one Carbon Credit representing one metric ton reduction of CO_2.

This system presents opportunities for investors as well. Individuals can invest in the carbon credit market in a few different ways, including direct investment in low-carbon companies or via exchange-traded funds (ETFs). Companies and individuals buy carbon offsets in the voluntary market in order to "offset" their carbon footprint. A carbon offset cancels out the CO_2 emissions that were produced in one place by reducing them in another place. A carbon offset represents one metric ton of carbon emissions. The purchase of an offset goes directly towards emissions reduction projects. When someone purchases an offset, that means a ton of carbon was removed or not emitted. This could be through installing solar panels or wind power system, direct air capture, or another method typically involving renewable energy.

The main difference between carbon credits and offsets is that a carbon credit gives one entity the right to emit carbon through the use of a "credit" purchased from another source. A carbon offset represents a more direct reduction of emissions, where the removal of carbon pollution by one entity helps offset the carbon emissions of another (Laurel Tincher 2023).

Quality offsets are certified by third parties who ensure that the carbon emissions being avoided or removed are legitimate. Requirements for certification are stringent to ensure that the offsets actually have a real impact. Examples of carbon offset projects might include solar power projects, wind farms, methane recapture operations, reducing deforestation, reducing the use of wood burning stoves and many such others. The negative side of carbon offsets is that they don't reduce one's own emissions and basically give people and companies permission to keep emitting carbon.

There have been long-standing concerns around the integrity of carbon credits. The Integrity Council on the Voluntary Carbon Market (IC-VCM), a multi-stakeholder and widely respected body, was set up as a successor to the Taskforce on Scaling Voluntary Carbon Markets (TSVCM), and tasked with defining a market-wide benchmark for high-integrity carbon credits, known as the "Core Carbon Principles" (CCPs). A first draft of the CCPs were published for consultation in mid-2022, with a final version published in late March 2023. The IC-VCM hopes credits can start to be assigned a CCP label from late 2023 (https://trove-research.com/commentary/core-carbon-principles-alignment-with-troves-carbon-credit-integrity-assessments/)

1.3.6 Carbon Sequestration, Carbon Sinks and CO_2 Equivalent

Carbon sequestration is the process of capturing, securing, and storing carbon dioxide from the atmosphere. The idea is to stabilize carbon in solid and dissolved forms so that it does not cause the atmosphere to warm. The process shows tremendous promise for reducing the human "carbon footprint". There are two main types of carbon sequestration: biological and geological (The Greenhouse Gas Protocol 2004). Carbon Sequestration refer to the storage of carbon that has the immediate potential to become carbon dioxide gas. Carbon Sequestration is the removal of carbon dioxide from the atmosphere and storage in another system, such as vegetation. If the carbon dioxide sequestered is more than the carbon dioxide emitted, the store is increasing and is known as a carbon sink. carbon sequestration is the long-term storage of carbon in plants, soils, geologic formations, and the ocean. Carbon sequestration occurs both naturally and as a result of anthropogenic activities. Significant interest has been drawn to the possibility of increasing the rate of carbon sequestration through changes in land use and forestry and also through geoengineering techniques such as carbon capture and storage (Selin 2023a, b).

Reservoirs that retain carbon and keep it from entering Earth's atmosphere are known as carbon sinks. For example, deforestation is a source of carbon emission into the atmosphere, but forest regrowth is a form of carbon sequestration, with the forests themselves serving as carbon sinks. The Kyoto Protocol under the United Nations Framework Convention on Climate Change allows countries to receive credits for their carbon sequestration activities in the area of land use, land use change, and forestry as part of their obligations under the protocol.

CO_2 equivalent is another important entity in the discussion of carbon emission. Eurostat Statistics explained, "A carbon dioxide equivalent or CO_2 equivalent, abbreviated as CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential". In other words, a CO_2-eq is a standard unit for counting greenhouse gas (GHG) emissions regardless of whether they are from carbon dioxide or another gas, such as methane. As we know, GHG emissions are mainly CO_2. However, there are other GHGs that contribute significantly to human-induced global warming such as methane (CH_4), nitrous oxide (N_2O), refrigerant gasses (HFCs, PFCs, and CFCs), sulphur hexafluoride (SF_6), water vapour (H_2O), and ozone (O_3) (https://greenbusinessbureau.com/green-practices/energy/scope-1-emissions/).

CO_2-eq are commonly expressed as million metric tons of CO_2-eq, abbreviated as MMTCDE. The CO_2-eq for a gas is derived by multiplying the tons of the gas by the associated GWP:

$$\text{MMTCDE} = (\text{million metric tons of a gas})^* \ (\text{GWP of the gas}).$$

For example, the GWP for methane is 25 and for nitrous oxide 298. This means that emissions of 1 million metric tons of methane and nitrous oxide respectively is equivalent to emissions of 25 and 298 million metric tons of carbon dioxide (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent#:~:text=A%20carbon%20dioxide%20equivalent%20or%20CO2%20equivalent%2C%20abbreviated,carbon%20dioxide%20with%20the%20same%20global%20warming%20potential).

1.4 Decarbonization

Decarbonization means a decrease in the specific amount of carbon (or CO_2) emitted per unit of primary energy consumed. Decarbonization is not only about limiting GHG emissions and conserving natural resources; it is increasingly just good business. Hence it becomes essential to reduce carbon emission. Decarbonization reduces the amount of gaseous carbon compounds released in an environment or process. "The word decarbonisation refers to all measures through which a business sector, or an entity—a government, an organisation—reduces its carbon footprint, primarily its greenhouse gas emissions, carbon dioxide (CO_2) and methane (CH_4), in order to reduce its impact on the climate".

In the EU, the transition to a low-carbon economy is estimated to create 1.2 million additional jobs by 2030 as per the European Commission, "Employment and Social Developments in Europe", 2019. Rewiring America, "Mobilizing for a Zero-Carbon America" reported that the decarbonization via mass electrification could create as many as net 25 million American jobs over the next 15 years". Decarbonization takes a relatively straightforward path which is not so easy. Each step in the path can pose significant challenges and requires technological, financial, organizational, and governance capacity. Fortunately, new solutions and financing models make decarbonized technologies more accessible, effective, and affordable than ever.

Achieving the Paris Agreement goal of limiting global warming to well below 2 °C requires a rapid decarbonization of the economy. According to most climate-economic models, this can only be done with the use of costly carbon-removal technologies (Fuss et al. 2020; IPCC 2018a, b). Decarbonization of industry and material production, in particular, requires technological and organizational change and large investments into new energy infrastructure and factories (Rissman et al. 2020; IEA 2020). GHG emissions from material production have risen from 5 Gt CO_2-equivalents (CO_2-eq) in 1995 to 11.5 Gt in 2015 (Hertwich 2021) and represent about 23% of global GHG emissions (Pauliuk et al. 2021).

Decarbonization helps organizations in the following ways that has been observed.

- Conserve resources and boost bottom lines
- Satisfy investors and other key stakeholders
- Ignite innovation and technological progress

- Stimulate organizational growth
- Grow industry influence, reputation, and brand
- Hire and retain top talent
- Building image in the society and set examples for others.

Increasingly, institutional investors, boards, and leaders see the value in decarbonization. Pressure is mounting for organizations to respond. For many organizations, the difficulty comes when asked to implement decarbonization strategies at scale. It is one thing to aspire to carbon neutrality or net-zero emissions and something else entirely to get there. Most organizations already understand why decarbonization is important while the key is to help them understand how to move from ambition to action (Schneider Electric 2021).

Given the anticipated slow pace of decarbonizing material production, the reduction of material demand through (1) more efficient use of materials at all stages of the material cycle and (2) the decoupling of services, such as mobility, from the number of material-intensive products, such as vehicles, may result in more immediate emission reductions.

Organizations must understand, from the beginning, what is their present status on carbon emission on the decarbonization pathway and what it is they aspire to achieve. Leaders across an organization must align on the vision and the strategy to achieve that vision. This is a foundational element to any program of change. Figure 1.4 demonstrates four phases of decarbonization pathway.

More and more people are switching to electric vehicles each year, which do not require decarbonizing at all, and modern internal combustion engines are seeing less carbon build up as fuel efficiency continues to increase and carbon residue in fuels continues to decrease.

Decarbonizing electricity and energy usage is a complicated challenge that will require a global effort to achieve. This will involve deep decarbonization, utilizing out-of-the-box energy resources and creating entirely different systems for how we generate and consume not just electricity but also energy in general. However, the electric vehicles and hydrogen fuels, etc. can fuel up the decarbonization transition at a faster rate.

In the building sector, decarbonization can be achieved through the energy efficiency measures focused on reducing the energy demand, reducing the energy consumption and increasing the use of low-carbon technologies, such as renewable energy sources. Decarbonization in the building sector involves the materiality of the built environment throughout their whole life cycle, users' energy habits and the performance and efficiency of the building and neighbourhood systems (European Commission 2019).

Fig. 1.4 Four phases of closed loop decarbonization pathway

1.5 Low-Carbon Technology

Energy efficiency refers to using less energy to perform the same task, that is, eliminating wastage of energy. Energy efficiency possess wider variety of benefits: reducing GHG emissions, reducing demand for energy imports, and lowering costs on a household and economy-wide level. It has been observed that 66% of industrial energy consumption spent in the heat applications, but the focus is often on electricity. With increasing energy intensity, the importance of heat applications for decarbonization in companies increases. For decades, the energy efficiency has been largely overlooked in early periods of energy transition planning. The energy efficiency should be more focused in the manufacturing and production context, as the sectors not only manufacture goods efficiently but also take into consideration its impact on other sectors and intended users. Low-carbon emitting technologies (LCET) are referred to as innovative technical solutions that are characterized by a low emission intensity, compared to state-of-the-art alternatives with a focus on environmental impact. They should act as an economic substitutional technology while fulfilling the initial promise of performance.

1.6 Circular Economy

Circular economy concept at present attracted the global attention as it is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible.

Circular economy promoted the use of materials at the end of its life cycle of its intended use. This helps in reducing the extraction of natural resources for new production processes. In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, thereby creating further value. This is a departure from the traditional, *linear* economic model, which is based on a take-make-consume-throw away pattern or *epcd2*, means, extract-produce-consume-dispose-deplete. This model relies on large quantities of cheap, easily accessible materials and energy. In a circular economy, things are made and consumed in a way that minimizes our use of the global resources, cuts waste, and reduces carbon emissions.

In the traditional practice for long time, materials from the Earth are extracted, products are made from them, consume them as per its intended use, and eventually throw them away as waste and deplete the resources—the process is linear. In a circular economy, by contrast, we stop waste being produced in the first place. The circular economy is a systems solution framework that tackles global challenges such as climate change, biodiversity loss, waste, and pollution.

Circular economy is a systems solution framework that tackles global challenges such as climate change, biodiversity loss, waste and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. Circular Economy could be understood in details with the definitions by researchers. There is no standard definition of circular economy, however, the most appropriate acceptable ones are compiled in Table 1.5. Circular economy must start at the conceptual level of a product or process. The materials, processes, products, resources required must be designed keeping the focus of longer lifetime of the product, minimum resources, namely, electricity, fuel, steam, heat, water, compressed air, to be required, with maximum productivity, tending to zero loss/rejection/wastes in process, sub-processes and products, effective reverse logistics and recycling, integration of supply and demand sides, utilisation of secondary raw materials in the same process, and a different process with a close loop materials cycles.

1.7 Case Studies: Circular Economy Implementation and Decarbonization by Carbon Footprint Reduction

It is clear that Circular Economy and decarbonization are complimentary to each other. If the concepts of circular economy are implemented, decarbonization will take place, on the other hand, the decarbonization process will stimulate the implementation of circular economy initiatives. The same may be observed in the following case studies.

Table 1.5 Definitions of circular economy (Source: Ghosh et al. 2022, p. 5–7)

The definition	Keywords	Reference
Circular economy is a systems-level approach to economic development and a paradigm shift from the traditional concept of linear economy model of extract-produce-consume-dispose-deplete (epcd2) to an elevated echelon of achieving zero-waste by resource conservation through changed concept of design of production processes and materials selection for higher life cycle, conservation of all kinds of resources, material and/or energy recovery all through the processes, and at the end of the life cycle for a specific use of the product will be still fit to be utilized as the input materials to a new production process in the value chain with a close loop materials cycles that improve resource efficiency, resource productivity, benefit businesses and the society, creates employment opportunities, and provides environmental sustainability	Systems-level approach; paradigm shift; epcd2; elevated echelon; zero-waste; resource conservation; changed concept of design and process; higher life cycle; conservation of resources; close loop materials cycles; resource efficiency; resource productivity; businesses and society; employment; environmental sustainability	Ghosh et al. (2022, p. 5)
The circular economy is an economy "where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized". The transition to a more circular economy would make "an essential contribution to the EU's efforts to develop a sustainable, low-carbon, resource-efficient, and competitive economy"	Value of products, materials, and resources; as long as possible; waste minimized; transition; sustainable; low-carbon; resource-efficient; competitive economy	European Commission (2018)
The circular economy as "an industrial system that is restorative or regenerative by intention and design. It replaces the "end-of-life" concept with restoration, shifts toward the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models". The overall objective is to "enable effective flows of materials, energy, labour, and information so that natural and social capital can be rebuilt"	Restorative; regenerative; replaces "end-of-life" concept with restoration; renewable energy; reuse; elimination of waste; superior design; effective flows of materials, energy, labour and information; natural and social capital, rebuilt	Ellen MacArthur Foundation (2013, p. 7)

1.7.1 Case 1: Going Global Partnership—Industry Academia Collaborative Grant Research Project for adoption of Circular Economy in SMEs to Reduce Carbon Footprints

The authors as the India Coordinator from ISWMAW have developed an innovative idea to involve the Small and Medium Sized industries in the Going Global Partnership - Industry Academia Collaborative Grant Research Project (GGP-IACGRP), funded by British Council and Aston University, UK. The personnel involved in the group activities, named, CESIP (Circular Economy Small Improvement Project) group develops the scopes from improvement in the Small and Medium Sized Enterprises (SME) based on the process mappings and data analysis in consultation with the Academic and Industry partners. CESIP group is a cross functional team may consist of 3–7 persons who are involved in the improvement project as well as one or two from the partner organization. The India Coordinator and the UK PI are the permanent member of each CESIP Group. Sixty SMEs are working in the project from West Bengal, Andhra Pradesh, Maharashtra, and Delhi in India and five SMEs in Birmingham, UK. Each of the SMEs will identify the leakage/loss/weakness in different areas e.g., wastes generation, cycle time, energy spent/wastes, water utilization, recycling, reverse logistics, substitution of expensive materials, material flow, changing processes to smarter ones, waste and WIP utilization, fuel used, boiler operation, steam, emission, system of closing the loop, productivity, green purchase, layout, space utilization and illumination, etc. develops at least three CESIP. The CESIPs are being developed based on the improvement area identification in process maps and components in Table 1.6. Most of the CESIPs will reduce carbon footprints. However, the calculation of carbon footprints will be carried out for each CESIP to understand the reduction in carbon footprints though it is a complicated one.

The project will run till the month of December 2023 when assessment of the extent of CE implementation measuring resource efficiency and reduction of carbon footprints (CF) with a total target of 10% reduction of CF from the February 2023 level in the SME units. Eleven number of academic institutions and industry/ researchers' associations have been working in the project as the partners, namely, Aston University, UK, International Society of Waste Management, Air and Water (ISWMAW), Kolkata, Jadavpur University, Kolkata, Federation of Small and Medium Industries (FOSMI), Kolkata, K J Somaiya Institute of Management (KJSIM), Mumbai, Sri Venkateshwara University, Tirupati, AP, Sri City Pvt. Ltd., Tirupati, AP, GITAM deemed to University, Visakhapatnam, Godavari Biorefineries Ltd., Mumbai, Centre for Responsible Business (CRB), New Delhi and Techno India University (TIU), Kolkata. The SMEs have already identified the CESIPs and started the improvement initiatives. A review is carried out each month for follow-up and monitoring the progress. It is expected that at least 70% of the targets of reduction of carbon footprints will be achieved. It is expected that each of the 60 SMEs will institutionalize the culture of adopting the circular economy concepts and will start getting benefits as applicable.

Table 1.6 Possible areas of CESIPs in circular economy implementation and decarbonization

Prevent big losses/leakages • Reduce breakdowns • Organized setup and adjustments • Reduce small stops • Increase speed • Reduce startup rejects • Zero production rejects • Zero-waste and reverse logistics • Zero emission • Reduce energy consumption • Reduce materials consumption • Reduce spillage • Reduce machine downtime • Reduce rejection • Reduce cycle time • Reduce process/machining time • Train on circular economy • Train on processes	Specific *defect* reduction by • Robust quality control Effective machine repair • Proper Effective documentation • Process standards • Understand customers' need • Accurate inventory levels Prevent environmental damage • Maximize waste treatment • Encourage recycling and reduce littering • Zero consumption of coal, HSD • Increase use of solar and other renewable energy sources • Increase resource circularity • Reduce waste and increase waste utilization
Reduce loss of *waiting* • Plan downtime or idle equipment • Reduce delayed set-up times • Improve process communication • Strengthen process control • Produce as per requirements • Remove idle equipment OR increase equipment utilization	Reduce *transportation waste* • Improve layouts—avoid large distance between operations • Effective material handling systems • Smaller batch sizes • Reduce multiple storage facilities • Robust design production systems
Reduce wastes due to *motion* • Improve workstation layout • Effective production planning • Improve process design • Dedicated equipment and machines • Clean operations • Appropriate production standards	Reduce *overproduction* • Unreliable process • Unstable production schedules • Inaccurate forecast and demand information • Customer needs are not clear • Long or delayed set-up times
Reduce *inventory waste* • Reduce overproduction • No delays in production • Zero defects in inventory • Reduce transportation	Encourage innovation • Poor communication • Involve people in workplace design and development • Lack of or inappropriate policies • Team training and retraining
10 Real-world industry 4.0 technologies Below are the top digital transformation technologies brought about by Industry 4.0: 1. Big data and analytics; autonomous robots 2. Simulation/digital twins; horizontal and vertical systems; industrial IoT (IIoT); cybersecurity technology; cloud; additive manufacturing; AI; augmented reality	

1.7.2 Case 2: Circulation of Waste as Secondary Raw Materials to Produce Different Products Including Cement Reducing Carbon Footprints

Citizens use different materials and generate municipal wastes comprising of different types of dry and wet wastes. Through a flow chart (figure a model is presented for understanding the circularity of products from the extraction of natural resources to the utilisation of the products when reaching at their end-of-lifetime).

Based on Fig. 1.5, the case study on coprocessing is described. Alternative fuels and raw materials (AFR) from waste can play an important role in contributing towards reducing the use of fossil fuel and costs while conserving natural resources, lowering global CO_2 emissions, and reducing the need for landfills. Co-processing in cement kilns is a technology that is practiced globally on large scale for environmentally sound and ecologically sustaining management of wastes from agricultural, industrial, and municipal sources. Wastes from households, shopping complex, gated community, commercial and business houses are collected by the municipal waste collectors daily using hand cart, motorized carts in municipalities in Odisha and west Bengal. Figures are shown from the collecting vehicles and materials recovery facilities in ward number 115, Ukil para, Paschim Putiary, Kolkata, and Rourkela city in Odisha.

The waste collectors visit each of the houses and collect dry wastes and wet wastes separately. The dry wastes are taken to the material recovery facility and each of the categories of wastes are separated manually stored in separate bins or locations. All the dry wastes separated in nearly 18–22 categories depending on the availability of wastes. The non-recyclable plastics and other wastes are also stored separately which has calorific value. Sometimes if those are little wet, are taken for drying in the sun. Each of the recyclable wastes, such as, plastics, papers, cans, textiles, metals, glass, cardboard and cartons, and many others are sold to the recycling plants. The non-recyclable plastics and other wastes are sent to cement plants to produce appropriate Refuse Derived Fuel (RDF) in the pre-process plants in

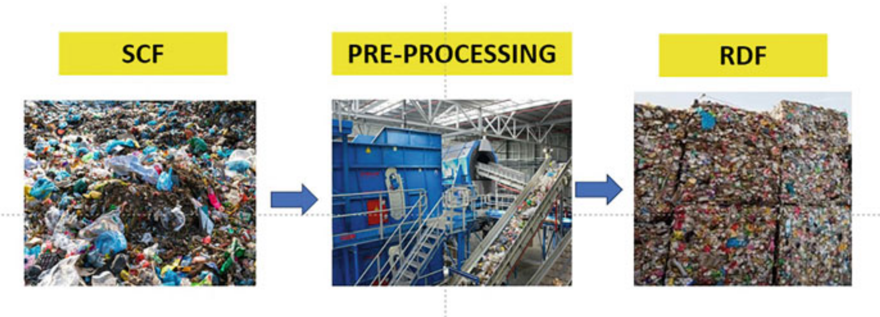

Fig. 1.5 Model to demonstrate the implementation of Circular Economy and Decarbonization (Source: Developed by the authors)

Fig. 1.6 Waste those may be co-processed in cement plants for cement production (Source: Ghosh et al. 2022)

the cement industries. Co-processing is an important technology for the sustainable management of hazardous and non-hazardous wastes derived out of Municipal, Industrial and Agricultural sources (Ghosh et al. 2022). Different types of wastes as demonstrated in Fig. 1.6 as available were separated for sending to the cement plants for co-processing. These materials go for pre-processing and coprocessing in the cement plants.

Pre-processing and coprocessing may be defined here for better understanding. Pre-processing may be defined as when alternative fuels and/or raw materials not having uniform characteristics must be prepared from different waste streams before being used as such in a cement plant. The preparation process, or pre-processing, is needed to produce a waste stream that complies with the technical and administrative specifications of cement production and to guarantee that environmental standards are met (UNEP 2011). Co-processing supports 3Rs and the waste hierarchy starting from waste reduction and least priority to landfilling. Co-processing is eco-friendly resource recovery option in waste management and comply with the Basel and Stockholm Conventions (Source: Guidelines on co-processing Waste Materials in Cement Production 2006). Alternative fuels are the wastes with recoverable energy value, used as fuels in a cement kiln, replacing a portion of conventional fossil fuels such as coal. Other terms include secondary, substitute, or waste derived fuels (UNEP 2011). Alternative fuels and raw materials (AFR) Inputs to clinker production derived from waste streams that contribute to energy and raw material requirements in the clinker manufacture.

Figure 1.7 demonstrate the photographs of wastes and RDF collected at bio mining sites and well as the Materials Recovery Facilities (MRF) in different municipalities in Odisha and West Bengal. There is the demonstration of commitment to implement circular economy and decarbonization using wastes.

There are huge number of examples of implement circular economy and decarbonization implementing water recycling, recycling and reducing waste materials in the process, materials and energy recovery, reducing energy usage,

Fig. 1.7 Dry wastes segregated at Rourkela biomining site (1) and MRF (2, 3, 5); and Jharsuguda Municipality MRF (3) for recycling and RDF preparation. and their sources those may be co-processed in cement plants for cement production (Source: Ghosh et al. 2022)

Fig. 1.8 Different wastes and their sources those may be co-processed in cement plants for cement production (Source: Ghosh et al. 2022)

Fig. 1.9 Different wastes and their sources those may be co-processed in cement plants for cement production (Source: Ghosh et al. 2022)

reducing machine idle running time, reducing cycle time, and changed processes and many other ways.

1.8 Conclusion

The transition to circular economy and net-zero emissions economies by decarbonization is a complex and difficult one, that cannot be solved by a handful of government agencies or using only one or two policy instruments. It would instead require a "whole-of-government" approach, where every ministry and all levels of governments, including states and cities, play a role. However, these are possible with pentagonal cooperation and desire of the governments, industries, academic and research organizations, non-government organizations, and general citizens. Implementation of circular economy and net-zero emissions economies by decarbonization need the understanding, awareness, and participation of multi-stakeholders in a nation. The policy, regulation, standard system, and effective governance are essential drivers for the transformation from traditional practices to the elevated echelon of requirements for circular economy and decarbonization which will lead to a sustainable society and environment.

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Part II

Policy Supports Toward Circular Economy

2 Policies and Practice of Sound Material-Cycle Society in Japan: Transition Towards the Circular Economy

Chika Aoki-Suzuki, Toru Nishiyama, Mizuki Kato, and Vesna Lavtizar

Abstract

The Japanese government has developed legislation to ensure appropriate waste management to tackle illegal disposal addressing growing production and consumption patterns, which caused increased waste generation leading to a lack of landfill sites. Japan has incorporated the Japanese concepts of a sound material-cycle society (SMCS) and the 3Rs (reduce, reuse, and recycle) to achieve waste minimisation and effective utilisation of resources and formulated finely tuned policy framework for establishing a SMCS and a fundamental plan. The framework consists of the Waste Management Act, the Act on the Promotion of Effective Utilization of Resources, specific recycling acts (containers and packaging, home appliances, food waste, construction and demolition material, end-of-life vehicles, and small home appliances), and other specific acts and policy tools on Promoting Green Procurement from multiple perspectives. Stakeholders in Japan have carried out a wide range of actions and introduced elemental technologies for a circular economy (CE) to respond to SMCS policies and sometimes surpass the levels required. These efforts have ensured that Japan has become one of the leading countries to develop a policy framework on resource efficiency and the circular economy. Japan has recently faced stagnation in primary resource consumption and resource productivity and hence, strengthening measures to achieve the transition to CE through its SMCS policies including addressing marine plastic litter. This chapter provides the most recent

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policy frameworks for SMCS/CE in Japan, with some illustrations of the best practices carried out by the private sector and Japanese local governments as outcomes. It concluded with the prospects for further elaboration of policies and practices to achieve a circular transition towards realising sustainable development in Japan.

Keywords

Sustainability · Recycling · Resource efficiency · Circular economy roadmap · Sound material-cycle society

2.1 Introduction

Japan has a long history of waste management as well as establishing a sound material-cycle society (SMCS). SMCS is the Japanese form of the circular economy (CE), based on the concept of the 3Rs (reduce, reuse, and recycle). The country has established a unique and consolidated policy framework and developed various types of policies and measures to achieve SMCS.

The Japanese government has developed legislation over the years responding to issues such as public health, pollution prevention, environmental protection, and effective resource utilisation, which led to the establishment of the SMCS (Ministry of the Environment, Japan (MOEJ) 2014).

The Waste Sanitation Act was enacted in 1900 to prevent the spread of epidemics, in which the responsibility of collecting waste was placed on local governments. It was succeeded by the Public Cleansing Act enacted in 1954 to address rapidly increased urban waste problems as a result of economic revitalisation after World War II and the accompanying urban population increase. This act aimed to promote the speedy removal of waste from cities and towns, restricting illegal dumping into rivers and oceans as well as open dumping to prevent public health problems and the spread of infectious diseases (MOEJ 2014). The Public Cleansing Act set out obligations of national and prefectural governments to provide financial and technological support to smaller local governments (at the city, town, and village level) for waste collection and disposal as well as stipulating residents' responsibility to cooperate with waste management (MOEJ 2014).

In the 1960s and 1970s, Japan had a mass consumption-disposal type economy and there was a considerable increase in the amount of waste generated, due to increased use of home appliances, and wider expansion of supermarkets and convenience stores. This resulted in more municipal waste. There was also a steep increase in construction waste and industrial waste including sludge, synthetic resin waste, and waste oil (MOEJ 2014). This industrialisation caused a range of serious problems, for example, illegal dumping, environmental pollution caused by hazardous waste such as organic mercury and cadmium as well as pollution with rapidly increased amount of single-use plastic (MOEJ 2014). In 1970, the Waste Management and Public Cleansing Act (Waste Management Act) was enacted to protect the living environment, including pollution control and public health improvement through developing basic waste management systems including defining two categories of waste—industrial waste and municipal waste—aiming at appropriate waste treatment (UNEP 2013; MOEJ 2014).

With further growth in production and consumption in Japan in the late 1980s to early 1990s, there were changes in both the amount and type of waste (for example, large-sized home appliances such as TVs, air conditioners, other wastes which are difficult to process properly, containers and packaging materials, and plastic bottles). Other major issues came up including a severe shortage of landfill sites and serious conflicts with citizens on the construction of new waste management facilities including incineration facilities and landfill sites (MOEJ 2014). Furthermore, large-scale illegal dumping and dioxins from waste incineration facilities had serious environmental impacts, causing a rise in anxiety among the general public on waste matters (MOEJ 2014). In 1991, the Waste Management Act was revised to add waste generation reduction by sorted collection and recycling as one of the purposes of the Act; additionally, the Act on the Promotion of Effective Utilization of Resources (Effective Resource Utilization Promotion Act) was enacted (MOEJ 2014).

In light of the above, Japan recognised the need to reduce waste and use resources more effectively, including resource circulation. This led to the development of the current policy framework for SMCS. There has also been steep growth in global resource demand and associated emerging environmental impacts including that of marine plastic litter, and considering this, Japanese society is currently making significant efforts to make the transition to CE.

This chapter provides an overview of the current Japanese system relevant to CE, including policies, efforts by the private sector, and some practices taken by cities. It firstly focuses on the basic policy frameworks for SMCS and CE in Japan including the fundamental plan for establishing SMCS and several specific recycling acts as well as recent policy development responding to materialising CE transition. The chapter also illustrates some of the best practices carried out by the private sector as outcome of the framework. The authors will also provide some concrete examples of the CE practices carried out by the local governments. By showing some quantitative results from Japan's efforts on CE, the chapter will conclude by looking at what the prospects are for further elaboration of policies and practices to achieve circular transition towards realising sustainable development in Japan.

2.2 Policy Framework on Sound Material-Cycle Society

Policy framework in Japan is made up of several pieces of legislation and a range of policy measures formulated across the whole lifecycle. The Basic Act for Establishing a Sound Material-Cycle Society and its fundamental plan form the basis for Japan's actions on CE in combination with the Act on the Promotion of Effective Utilization of Resources and the Waste management and public cleaning act. Under the Basic Act and plan as an umbrella policy for SMCS, several policies have been formulated including six specific recycling acts (containers and packaging, home appliances, food, construction materials, end-of-life vehicles and small home appliance) and the green purchasing act. Japan also enacted a variety of specific recycling acts to ensure the effective use of resources, to reduce waste generation, and to protect the environment, collaborating with private sector entities to advance recycling activities through the development of recycling technologies. (MOEJ 2014) This robust policy framework for SMCS covers all product lifecycle stages as shown in Fig. 2.1.

2.2.1 The Basic Act and Its Fundamental Plan for Establishing a Sound Material-Cycle Society

Under the Basic Environment Act enacted in 1993, the government established the Basic Act for Establishing a Sound Material-Cycle Society enacted in 2000 to shift from a mass production-consumption-disposal economic system to SMCS. Through the implementation of the 3Rs and proper waste management, the government aims to reduce natural resource consumption and lower the environmental impact. The huge amount of waste that is generated must also be addressed, as well as the need for further recycling promotion, difficulties with waste management facilities, and illegal dumping (MOEJ 2014). The Basic Act defines a "Sound Material-Cycle Society" in its Article 2(1): "a society in which the consumption of natural resources will be conserved and the environmental load will be reduced to the greatest extent possible, by preventing or reducing the generation of wastes, etc. from products, etc., by promoting proper cyclical use of products, etc. when these products, etc. have become circulative resources, and by ensuring proper disposal of circulative resources not put into cyclical use" (MOEJ 2000). In this context, the priorities for resource recycling and waste management were also determined in the act as (1) reduction; (2) reuse; (3) recycling; (4) thermal recovery; and (5) proper disposal. The Fundamental Plan for Establishing a Sound Material-Cycle Society was also established in 2003 as an umbrella action plan towards SMCS (MOEJ 2013) for comprehensive and deliberate promotion measures. This plan sets a mid- to long-term direction for the establishment of SMCS in Japan and is reviewed and revised by the government every 5 years. The current plan was adopted in 2018 and is the fourth one so far (MOEJ 2018a). The Fundamental Plan sets out seven pillars for implementing measures: (1) Integrated Measures towards a Sustainable Society; (2) Regional Circulating and Ecological Sphere; (3) Resource Circulation throughout the Entire Lifecycle; (4) Proper Waste Management and Environmental Restoration; (5) Disaster Waste Treatment Systems; (6) International Resource Circulation; and (7) Sustaining Fundamentals for 3Rs and Waste Management through Technologies, Human Resources and Awareness-Raising, and Information and Databases. For the third pillar on Resource Circulation throughout the Entire Lifecycle, Japan promotes businesses related to resource-efficient design and the 2Rs (reduce and reuse). The plan also sets out some prioritised areas such as plastics (including plastic resource circulation strategy), biomass (food loss and waste),

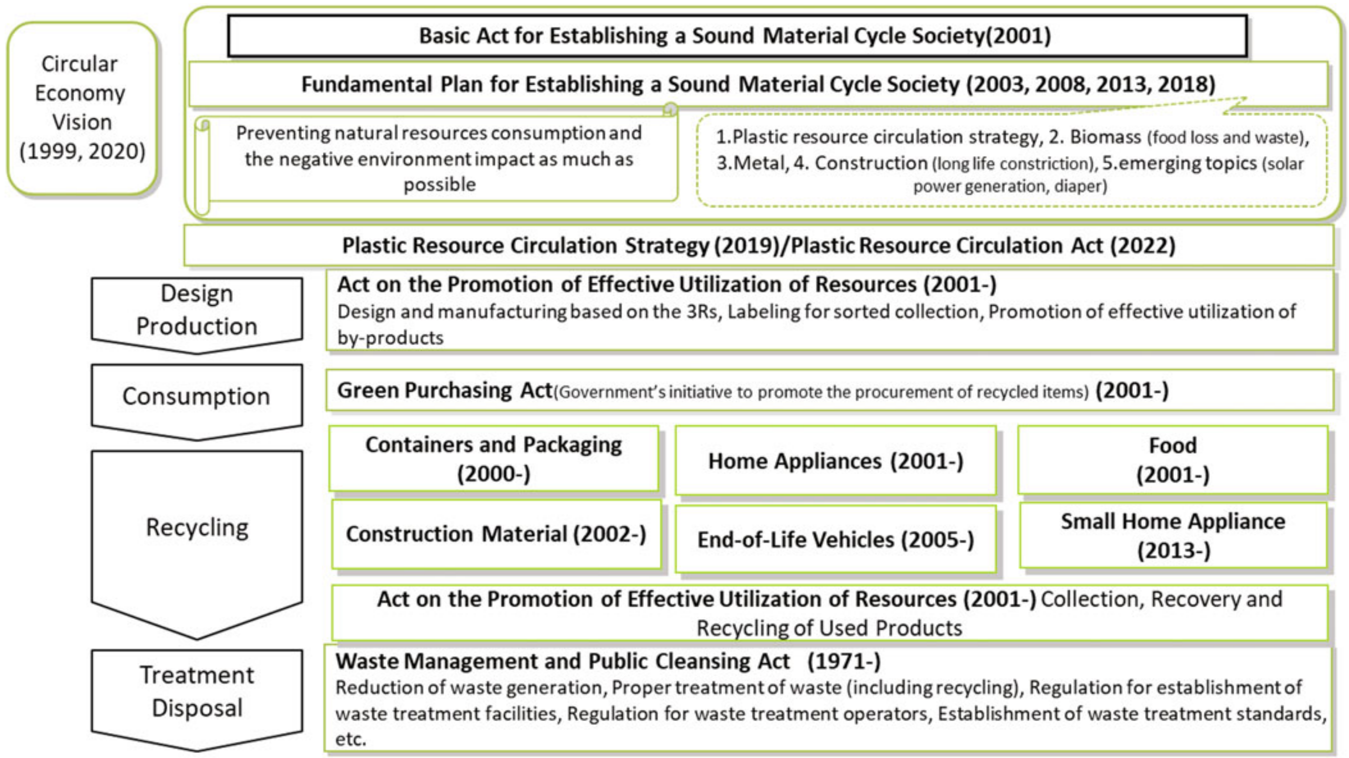


Fig. 2.1 Japanese policy framework on SMCS. (Source: developed by authors based on Ministry of the Environment (MOEJ) and Ministry of the Trade and Industry (METI); Note: Year: year of enactment)

metals, construction materials (long-life construction), and other emerging topics (solar power generation, diaper recycling).

The government monitors the progress of the plan using material flow analysis as well as an indicator set. The indicator set consists of 151 indicators including four headline material flow indicators with policy targets. The targets for FY2025 are:

- Resource productivity = GDP/Input of natural resources, etc. = JPY 490,000/t (roughly double that of FY2000)
- Cyclical use rate (resource base) = Amount of cyclical use/(Amount of cyclical use + Input of natural resources, etc.) = 18% (approx. 80% increase from FY2000)
- Cyclical use rate (waste base) = Amount of cyclical use/Generation of waste, etc. = 47% (approx. 30% increase from FY2000)
- Final disposal amount = the amount of landfilled = 13 million tonnes (77% reduction from FY2000)

The time series trend of resource productivity, cyclical use rate (resource base), and final disposal amount is shown in Sect. 2.2.4.

2.2.2 Major Policies Relevant to CE Under the Framework of SMCS

2.2.2.1 Act on the Promotion of Effective Utilization of Resources

The purpose of this act is to promote recycling in various industries. The act sets out some basic rules for environmental considerations in product design and manufacturing stages which would contribute to waste management, as well as giving guidance on the systems for independent waste collection and recycling by business operators (MOEJ 2014). This legislation does not determine detailed procedures on how to recycle a specific material. Rather, it describes the general goals and guidelines for various industries. The law designates ten industries and 69 products for which 3R measures are stipulated at the product manufacturing stage and at the design stage, identification labels for sorted collection, and the establishment of voluntary collection and recycling systems by businesses.[1] Electrical industries have designed and implemented recycling systems for PCs and small rechargeable batteries based on the act.[2]

[1]Ministry of the Trade, economy and Industry, Act on the Promotion of Effective Utilization of Resources https://www.meti.go.jp/policy/recycle/main/admin_info/law/02/index.html (accessed Feb. 2023).

[2]In FY2017, according to PC3R Promotion Association, 410,000 items (2.8 thousand tonnes) related to PCs and displays were collected from households and business users. Excluding reused items, 73.6% of this amount was recycled. According to Japan Portable Rechargeable Battery Recycling Center, 1.2 thousand tonnes of small rechargeable batteries were collected. Recycling rates differ depending on the kind of battery.

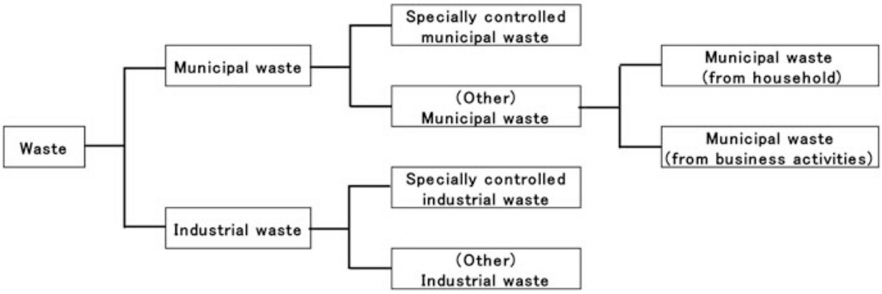


Fig. 2.2 Waste categories under the Waste Management Act (1971). (Source: Authors based on Ministry of the Environment, Japan)

2.2.2.2 The Waste Management and Public Cleansing Act

The Waste Management and Public Cleansing Act sets out the definitions of waste, responsibility for waste treatment, and procedures on waste treatment for implementing waste management (MOEJ 1970).

The Waste Management Act classifies waste into two categories (Fig. 2.2). The first is industrial waste discharged from industrial activity that is categorised into 20 categories, such as sludge, waste oil, ash, etc. Industrial waste does not cover all waste generated from business activity. Specially controlled waste includes infectious waste, fly ash from incinerators, flammable oil, strong acid and alkaline, and waste containing asbestos, PCB (polychlorinated biphenyl), dioxins, and other hazardous chemicals and heavy metals. The second category is municipal waste which means waste other than industrial waste mainly discharged from households and business such as offices and shops.

The largest difference between municipal waste and industrial waste is responsibility for waste management. Each local government (city, town, and village) is responsible for collection and treatment of municipal waste. Local governments are required to prepare municipal waste treatment plan, construct treatment facilities, and conduct collection and treatment operations. They must also pay the cost of these operations from their administrative budget. Some local governments collect tipping fees from households, mainly by selling designated trash bags. Many local governments also charge for municipal waste from business activities and large/oversized bulky waste from households such as furniture. In general, local governments have promoted recycling to reduce waste generation by establishing a number of waste categories for source segregation (Table 2.1).

For industrial waste, the industry/company which generates the waste must take primary responsibility for treating it. This is generally contracted out to licensed waste transport/treatment operators. Even after waste is transferred to the licensed contractor, the generator is still responsible until the waste is finally disposed of in a landfill site or recycled as other material. Manifest slips must be issued for each waste transfer to ensure the waste is transported and treated appropriately, so that the generator can fulfil their responsibility through the system. The Waste Management Act sets technical standards of treatment, such as incineration and landfill as well as

Table 2.1 Waste category for Yokohama City (population about 3.7 million)

Number of category	Items
1	Burnable garbage
2	Dry-cell batteries
3	Spray cans
4	Non-burnable garbage
5	Plastic containers and packaging
6	Can
7	Bottles
8	PET bottles
9	Small metal items
10	Paper (newspaper, cardboard, magazine, milk carton, other)
11	Used cloth/textile
12	Oversized garbage (bulky waste)

Source: Yokohama City (https://www.city.yokohama.lg.jp/kurashi/sumai-kurashi/gomi-recycle/ongen/pamphlet/wakedashi.html (Accessed Feb 2023))

conditions for licencing the waste transporters and treatment operators. Licences for waste management should be issued by the local government (prefectural or city/town/village level) at the location of business.

2.2.2.3 Act for the Promotion of Sorted Collection and Recycling Containers and Packaging

This act aims to reduce containers and packaging waste by promoting recycling of municipal waste. This is the first act in Japan which applies extended producer responsibility (EPR). The "producers" defined in this act include both manufacturers of containers and packaging and users of containers and packaging such as manufacturers of food and other consumer goods, importers of goods, and retail shops that additionally provide plastic shopping bags and other containers and packaging. Containers and packaging made of glass bottles, PET bottles, paper and plastic, generated as municipal waste, are targeted in the act. Even if a producer takes the responsibility for recycling, collection of municipal containers and packaging waste is always carried out by the local government.

The Japan Containers and Packaging Recycling Association (JCMA)[3] was established as an intermediary between the local government and recycling companies for transaction of containers and packaging waste. The JCMA, as a designated corporation based on the act, coordinates the recycling of waste plastic packaging and containers as entrusted by local governments on the basis of commissions from producers, as well as information dissemination and awareness-raising.

[3] Japan Containers and Packaging Recycling Association https://www.jcpra.or.jp/ (accessed Feb. 2023).

In the case of plastic packaging, in FY2019, the association managed a total of 663,192 tonnes out of which 439,165 tonnes of was recycled.

Column: Guidance for Design for PET Bottles by Industrial Association
Relevant to the Act for the Promotion of Sorted Collection and Recycling Containers and Packaging, voluntary design guidelines for PET bottles have been issued by the Council for PET Bottle Recycling since 1992.

The first version in 1992 included the following basic principles for a better recyclability:

- Transparent bottle with limited colour is desirable.
- Label should be easily removed from the bottle. Paper label with adhesive should not be used.
- Ring part of aluminium cap should not remain to the bottle.
- PVC should not be used for label and liner of cap.

These principles were elaborated in the latest eighth version in 2018. The most important points had appeared until 2001 including limitations on transparent bottles with perforated plastic labels and prohibition of aluminium caps. PET bottles, caps (PE or PP), and labels can be mechanically separated using the difference of specific gravity.

These guidelines contribute to maintaining a high recycling rate for PET bottles in Japan (84.6% in FY2018).

Reference: Website of the council of PET bottle recycling[4]

2.2.2.4 Act on the Recycling of Specified Kinds of Home Appliances

This act aims to reduce waste and promote the effective use of resources through recycling useful parts and materials from home appliances (air conditioners, televisions (CRT, LCD, and plasma), refrigerators and freezers, washing machines, and clothes dryers) discarded by households and offices. The act also intends to reduce the waste treatment burden for local governments that have to deal with an increase in disposal of large home appliances and must appropriately treat the hazardous substances that can be contained in these appliances (such as CFC and heavy metals).

[4]The council of PET bottle recycling http://www.petbottle-rec.gr.jp/english/design.html (accessed Feb. 2023).

For this purpose, 47 recycle facilities (as of 1 October 2016)[5] have been established by way of a collaboration between home appliance manufacturers and recycling companies. Consumers have a responsibility to pay a recycling fee when they dispose of these home appliances. Most of them are collected at retail stores which have a responsibility under the act. In FY2021,[6] the number of four types of waste home appliances collected at designated nationwide collection points was approximately 15.26 million units. The recycling rate[7] was 92% for air conditioners, 72% for CRT TVs, 85% for LCD and plasma TVs, 80% for electric refrigerators and freezers, and 92% for electric washing machines and clothes dryers.

2.2.2.5 Act on Promotion of Recycling and Related Activities for Treatment of Cyclical Food Resources

This act aims to reduce food waste and promote recycling. The entities covered under this act are food manufacturers and processors, distributers, retail stores, and restaurants including hotels. The act requires them to report food waste generation and recycled amount annually to the government. Under the act, producing animal feed, producing fertiliser, and anaerobic digestion to generate methane gas are recommended. In FY2016,[8] food manufacturers and processors generated 16.17 million tonnes out of a total of 19.7 million tonnes of food waste, and 81% of this waste was recycled. Distributers, retail stores, and restaurants including hotels generated the other 3.53 million tonnes, with 25% of this waste being recycled.

Column: Guidance for DfE by Industrial Association

In Japan, the "Products Assessment Manual" for home appliances has been issued by the Association for Electric Home Appliances (AEHA)[9] since 1991. The association comprises 29 manufacturers and 11 home appliances associations. The manual outlines guidelines for the effective evaluation of eco-design procedures in electronic appliances. The latest fifth version consists of 15 categories of evaluation points:

1. Reduction of resource usage and waste generation
2. Usage of recycled materials and parts

(continued)

[5]Association for Electric Home Appliances https://www.aeha.or.jp/action_of_recycling/plant/ (accessed Feb. 2023).

[6]Status of home appliance recycling https://www.aeha-kadenrecycle.com/resaultreport/ (accessed Feb. 2023).

[7]Recycling rate = Recycled/collected and treated under the act.

[8]Ministry of Agriculture, Forestry and Fisheries. Annual food waste generation and food recycling rate, http://www.maff.go.jp/j/shokusan/recycle/syokuhin/kouhyou.html (accessed Feb. 2023).

[9]Association for Electric Home Appliances (AEHA) https://www.aeha.or.jp/global/about.html (accessed Feb. 2023).

3. Reduction and recycling of packaging
4. Reduction of environmental burden during production process
5. Efficiency of transportation
6. Saving energy and consumables during utilisation
7. Elongating product life
8. Efficient collection of end-of-life products
9. Usage of materials that are easy to recycle
10. Easy to decompose and separate for manual recycling process
11. Easy for shredding by avoiding hard materials, magnet, and oil
12. Environmental protection by limiting or prohibiting environmentally hazardous materials
13. Safety for human injury
14. Providing information for utilisation, repair, and recycling
15. Lifecycle assessment (LCA) for environmental burden

AEHA has also published labelling guidelines for packages, rechargeable batteries, plastic and metal parts materials, and decomposing instructions. These guidelines have contributed to improving recyclability of the products.

One key to success is that the manufacturers are involved in establishing and operating recycling facilities. Issues related to dismantling and recycling of the products at recycle facilities can be directly fed back to the manufacturers and reflected in eco-design for better recyclability. The association released a report of feedback cases in 2009.[10]

Reference: AEHA website

2.2.2.6 Construction Material Recycling Act

This act aims to ensure appropriate management and to promote recycling of construction and demolition waste. The act requires companies in the sectors of construction, demolition, renovation, or civil work to segregate and recycle waste materials generated in their work, such as concrete, asphalt, steel, and wood.

The reason for the act was the large amounts of construction and demolition waste and illegal disposal. In FY2017,[11] such waste amounted to 84 million tonnes, which was 21.8% of the total industrial waste volume, causing a huge burden on landfill sites. Moreover, a certain amount of construction and demolition waste had been illegally disposed of.

[10] Design requests and examples of improvements from home appliance recycling plants https://www.aeha.or.jp/environment/pdf/RPR-ECD_Zirei.pdf (accessed Feb. 2023).

[11] Ministry of the Environment, Japan. Status of industrial waste generation and treatment (*Sangyo haikibutsu no haisyutsu oyobi syori jyokyo tou*) https://www.env.go.jp/recycle/waste/sangyo.html (accessed Feb. 2023).

In FY2012,[12] 74.8 million tonnes of construction and demolition waste was generated, and 94% of the waste was recycled as other materials.

2.2.2.7 Act on the Recycling of End-of-Life Vehicles

This act aims to reduce waste and make effective use of resources by clarifying the roles of automobile users, automobile manufacturers and importers, take-back companies, CFC collectors, dismantlers, and shredders. Traditionally, end-of-life vehicles (ELV), which contain valuable resources and useful metals and parts, have been recycled through market transaction between businesses. However, the remaining parts of the ELV such as automobile shredder residue (ASR), CFCs and hydrofluorocarbons (HFCs), and air-bags are very difficult to recycle, and these three items have not been well managed and recycled. The ELV act stipulates that car manufacturers and importers are to be responsible for treating these three items appropriately. When consumers buy a new car, they must pay a recycling fee which is managed by the Japan Automobile Recycling Promotion Center (JARC). JARC then provides funding to designated treating and recycling companies.

In FY2017, 726 tonnes of CFCs and HFCs were recovered and 583,000 tonnes of ASR were treated (Japan Automobile Recycling Promotion Center 2017).

2.2.2.8 Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment

This act aims to promote recycling of electrical and electronic equipment other than home appliances, which have been recycled under the Home Appliances Recycling Act. This includes mobile telephones and land-line telephones, cameras, audio-visual equipment, and electrical cooking equipment. Local government should collect them separately from other waste and send collected items to designated recycling companies. However, enforcement on items to be collected depends on each local government. In FY2015(Ministry of Internal Affairs and Communications 2018), 70% of local governments (1219 local governments out of 1735), covering 86.8% of the Japanese population, had already started separate collection in accordance with this act. A total of 93% of the 67,000 tonnes of collected items were recycled, including thermal recovery of plastic.

2.2.2.9 The Act on Promotion of Procurement of Eco-Friendly Goods and Services by the State and Other Entities

The Act on Promoting Green Procurement was enforced in 2001 as one of the individual laws under the Basic Act for Establishing a Sound Material-Cycle Society. Since the Basic Act is a key CE legislation in the country, it can be considered that the Japan's Green Public Procurement policy has been in line with the CE policy framework.

[12] Ministry of Land, Infrastructure, Transport and Tourism, Survey results of current status of construction by-products, http://www.mlit.go.jp/sogoseisaku/region/recycle/d02status/d0201/page_020101census.htm (accessed Feb. 2023).

This act aims to stimulate public procurement of and provide information on goods and services that contribute to reducing negative environmental impacts. Under the act, green procurement is defined as “a practice whereby purchasers seek to procure goods and services with reduced environmental loads throughout their lifecycle with consideration of their necessity, from suppliers who make constant efforts to be environmentally conscious” (MOEJ 2017a).

The act defines that green public procurement is mandatory for state and incorporated administrative agencies without specific quantitative targets. This is expected to contribute to promoting a shift in demand to environmentally friendly goods and services in society while considering proper use of the budget (MOEJ 2017a). Local governments and local incorporated administrative agencies are required to implement measures aimed at shifting demand to environmentally friendly goods and services on a voluntary basis, in accordance with the natural and social conditions of their local areas (MOEJ 2017a). Business operators and citizens (Article 5) should endeavour to select environmentally friendly goods and services to the extent possible when purchasing, leasing, or receiving the provision of services (MOEJ 2017a).

The number of designated procurement items in 2020 was 275, belonging to 22 categories which dramatically increased from 101 items in 14 categories in 2001. The categories include Paper, Home Electronic Appliances, Interior Fixtures and Bedding, Stationery, Air Conditioners, Work Gloves, Office Furniture, Water Heaters, Other Textile Products, Imaging Equipment, Lighting, Facilities, Computers, Vehicles, Stockpiles for Disaster, Office Equipment, Fire Extinguishers, Public Work Projects, Mobile Telephones, Uniforms/Work Clothes and Services (MOEJ 2017a).

In the implementation process of this Act, the Eco Mark (see description below) was established. In principle, use and referencing to environment-related labels by third parties are suggested by the Act on Promoting Green Procurement. The Eco Mark thus is commonly referred and used in the procurement process to certify that the procured products are in line with environmental requirements. The Eco Mark criteria is basically considered as equivalent to, or better than, the Act on Promoting Green Procurement criteria with some exceptions (MOEJ 2017a).

Column: Labelling (Eco Mark) and Certification

Eco Mark

The Eco Mark is an environmental label, which was launched in 1989 and is currently managed by Japan Environment Association Eco Mark office.[13] The label aims to change consumer behaviour for making more sustainable choices on products and services, as well as to encourage companies to improve their environmental performance for a sustainable society. The label

(continued)

[13] Japan Environment Association Eco Mark office https://www.ecomark.jp/(accessed Feb. 2023)

can be placed on products with less impact on the environment throughout their lifecycle from "production" to "disposal" that could be useful for environmental conservation. The association comprehensively assesses environmental impacts throughout the product lifecycle. There are several environmental evaluation factors that are mainly considered at each stage of the product life: "resource extraction", "production", "distribution", "consumption", "recycling", and "disposal". The number of registered products is 50,111 which also includes 4150 registered facilities (such as retail stores, hotels and restaurants) as of February 2023.

Eco Mark recently published a policy for plastics resource circulation and circular economy in February 2020. Four key policies and measures are defined below:

- Develop evaluation criteria to promote the reduction and reuse of plastics, expand the use of bio-based plastics, and increase the use of recycled plastics;
- Do not certify single-use plastic bags as "Eco Mark products for appropriate resource use";
- Certify biodegradable plastics only when they are used in the environment, difficult to collect, and when their biodegradability is ensured;
- Expand product-service systems, such as sharing services for reducing the environmental impact of society as a whole.

Eco Mark and the Act on Promoting Green Procurement are complementary relationships, so it is expected that the act's procurement policy direction will also move forward to create a circular loop for plastics.

Voluntary certification on products with recycled materials by local governments[14]

In Japan, recycled product certification systems have been established by many local governments (more than 35 prefectures out of the total 47 prefectures in Japan) to promote the use of recycled resources and waste reduction. Under this system, products are certified by local governments in terms of its use of recycled resources that meet certain quality and safety criteria as well as whether the recycled resources are generated in the local area.

In certifying process of products, local governments generally check the following items to certify: production amount, operator, sales place, type and usage rate of recycled resources, product specification, relevant other

(continued)

[14] Database on environmental label and so on https://www.env.go.jp/policy/hozen/green/ecolabel/c01_01.html(accessed Feb. 2023).

legislation, quality status (acquired standards and eco-labelling), environmental safety, product testing, and factory inspection results. The certified recycled products are diverse, such as toilet paper, stationery goods, construction materials, gardening equipment, and office furniture that are made of recycled materials.

2.2.2.10 The Plastic Resource Circulation Act

Following the national Plastic Resource Circulation Strategies (MOEJ, 2019) (see the details at Sect. 2.2.5.1), the Plastic Resource Circulation Act was enforced in 2022. This act addresses whole lifecycle of plastics (i.e., from designing products to disposing plastic waste) and involves all stakeholders in promoting “3R+Renewable” and increasing circularity. To promote circulation of plastics in a comprehensive and planned way, basic policy of this act consists of the following three measures.

- Develop guidelines for design for the environment for manufacturers and establish a mechanism to certify products designed in accordance with the guidelines. The government procures preferentially the certified products (under the Act on Promoting Green Procurement).
- Set criteria for retailers and service providers to reduce single-use plastics.
- Improve systems of separation, collection, and recycling of plastic waste by municipalities and private sectors.

2.2.3 Eco Town Programme

The Eco Town Programme started as a result of policies on the 3Rs, as well as industrial policies developed to address social and economic objectives in an integrated way. The programme promoted industrial development and regional revitalisation in Japan through resource recycling, based on the “Zero Emission Concept” proposed by the United Nations in 1994, which aims to reduce all types of waste to zero through the mutual use of resources (MOEJ 2018b).The first eco-town project was initiated in 1997 in Kitakyushu City (see the Kitakyushu City case study below) to support local innovation and entrepreneurship related to recycling activities and zero-emission strategies. The government system providing subsidies for eco-towns was discontinued in 2005, currently, 26 eco-towns are registered in Japan. After the subsidy system had finished, several government programmes were implemented to support the improvement and development of eco-towns, which is linked with the Regional-CES explained in the next section.

The criteria for eco-town establishment (Higuchi and Norton 2008) is as follows:

(a) Companies associated with eco-towns shall be sustainable and aim at zero emissions.

(b) Activities of eco-towns shall be unique (not just a copy of each other), to promote creativity and innovation. They must also include some novelties that can apply to other locations.
(c) Eco-towns receive a certain amount in grants, depending also on their innovativeness that they shall use for material assets and equipment, as well as for networking, information gathering, and promotion activities.

The background to the eco-town initiative was the need to revitalise industrial regions which had to deal with industries being moved overseas (MOEJ 2018b). During the rapid economic growth in the 1960s and 1970s, environmental pollution had also become an emerging issue in Japan. Japanese industries such as mining, steel and chemicals, which had caused pollution, also developed environmental protection technologies to use for themselves. By utilising such technologies, some regions developed environmental businesses related to resource circulation and pollution prevention technologies, making use of the existing infrastructures and businesses. Below are listed some examples of eco-towns.

2.2.3.1 Akita Region

Akita region, in the northern part of Japan, was the location for many non-ferrous mining sites. DOWA[15] was one of the companies which had mining and smelter operations in the region. After closing down the last mining operation in 1994, DOWA began recovering minerals, mainly treating e-waste such as printed circuit boards and mobile phones. The smelter for recycling can recover as many as 22 different kinds of elements such as Au, Ag, and Cu. DOWA has also established a recycling facility for home appliances in accordance with the Home Appliances Recycling Act, a soil remediation facility, waste incinerators, and controlled landfill sites, thereby contributing to international and domestic resource circulation and appropriate waste management.

2.2.3.2 Kitakyushu Eco-town

Kitakyushu Eco-town is supervised by an industry–academia–government coalition (Kitakyushu Eco-town Project 2018). It is one of the first eco-town projects approved by the Japanese government and is also the largest such eco-town in the country (Premakumara 2015). The eco-town started its operations with PET bottle recycling, and then over time, recycling activities greatly expanded (Shiroyama and Kajiki 2016). Today there are about 29 small to medium-size environmental industries and 16 practical research institutions attached to Kitakyushu Eco-town that are practising or developing and testing new recycling technologies (Premakumara 2015). Kitakyushu City also initiated a commercial wind power generation project in the eco-town, the first of its kind in Japan.

Kitakyushu Eco-town comprises three areas, each carrying out different activities (Higuchi and Norton 2008; Kitakyushu Eco-Town Project 2018):

[15] https://www.dowa-eco.co.jp/(accessed Feb. 2023).

1. “Kitakyushu science and research park” links local and international academic and research centres to carry out relevant research and provides teaching and training.
2. “Practical research area” is a creating centre for environmental industries, where organisations perform research and development for cutting-edge environmental technologies. This area includes also the “Eco-town Centre” providing education, exchanges of information, and engagement with local citizens.
3. “Comprehensive environmental industrial complex” is made up of recycling industries and venture businesses. A number of projects are taking place, including recycling of the following items and materials: wood, paper, empty beverage containers, vending machines, cooking oil, food, office equipment, automobiles, home appliances, fluorescent light tubes, slot machines, sludge, metal, medical instruments, mixed construction waste, and more (Kitakyushu Eco-Town Project 2018).

The eco-town became a hub for CE-related innovations, and a place where companies, universities, institutes, and governments collaborate on developing and promoting technologies relating to the environment and recycling (Shiroyama and Kajiki 2016).

2.2.4 Regional Circulating and Ecological Sphere (Regional-CES)

Regional-CES is a comprehensive approach, which provides a solution to local communities, for achieving SDGs by practising a circular and low-carbon economy, increasing regional resilience and well-being of the inhabitants. This is achieved in a way that utilises the best assets and potentials for circularity in that particular region. It results in the decentralisation of the region and advances a self-reliant society living in harmony with nature (Takeuchi et al. 2019). The Ministry of the Environment in Japan set out the Regional-CES concept in its fifth basic environment plan to serve as the foundation for developing the country’s future environmental policies (MOEJ 2018c, Takeuchi et al. 2019).

The first step to establish a Regional-CES is to recognise the unique characteristics of the region, to re-discover regional resources, and to use them optimally and sustainably (MOEJ 2018c). A schematic representation of Regional-CES is presented in Fig. 2.7. The countryside provides natural resources and ecosystem services, such as food, water, timber, renewable energy, water purification, and control of natural disasters. Urban areas, however, carry out economic activities and provide funds and human resources. In this way, resources circulate within each region and are exchanged with neighbouring regions. This contributes to the revitalisation of decentralised yet connected local societies and establishes harmonious co-existence between urban and rural areas. This kind of symbiosis and exchange between different geographies makes the most effective use of resources (Takeuchi et al. 2019; MOEJ 2018c; Takeuchi 2020).

The CES can be established in a regional or local area, depending on the resources in circulation. For example, a CES for household waste could be established on a community level, while for rare metals, regional circulation is more suitable (Takeuchi 2020).

One of the examples of regional-CES implementation along the SDGs is Shimokawa Town in Hokkaido (Kataoka et al. 2018). The primary activity in Shimokawa is forestry and by applying the Regional-CES concept, the town was able to establish sustainable forest management that maximises the use and circulation of its forest resources. This created additional value in all economic, social, and environmental dimensions. The citizens developed a so-called Grand Design, a public-led scheme with the Regional-CES as a foundation to improve the well-being of the community and ensure environmental sustainability. The results were shown in revitalisation of the local economy by promoting a sustainable forestry industry, which includes traditional forestry operations, production of local wooden products, and using forest biomass for energy production. This energy production method allowed the town to raise its local thermal energy self-sufficiency rate from 9% in 2010 to 49% in 2016, cutting CO_2 emissions by 18% across the region. To use all forestry materials efficiently, including waste, the town uses timber remnants generated during wood processing as fuel for woody biomass boilers. Unformed charcoal is used as a soil enhancer or to melt snow. Once trees are cut down, the Sakhalin fir needles left behind in the forest are used to make essential oils, which a private company uses to make aromatherapy products. Shimokawa also offers a 15-year environmental education programme related to forests for students from preschool through high school.

Shimokawa Town implemented numerous projects to increase the well-being of its residents. The implementation of the Regional-CES in Shimokawa's Ichi-no-Hashi biovillage brought outstanding results to revitalise the district. The biovillage attracted new companies, job opportunities, and younger people and significantly increased income from forest and wood related activities. The well-being of the citizens in Shimokawa also increased, as life there became more convenient and lively. The exceptional results that Shimokawa Town achieved across environmental, societal, and economic areas earned the town Japan's first SDGs Award. The widest impacts were achieved in SDG 15 (life on land), SDG 12 (responsible consumption and production), SDG 3 (good health and well-being), SDG 4 (quality education), SDG 7 (affordable and clean energy), SDG 13 (climate action), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation and infrastructure), and SDG 11 (sustainable cities and communities).

2.2.5 Recent Policy Measures for CE and SMCS

2.2.5.1 Plastic Resource Circulation Strategy

Responding to the growing international momentum of addressing marine plastic waste, the Japanese government formulated a national plastic resource circulation strategy in June 2019.

The strategy has several aims: to solve resource and environmental issues concerning plastics in Japan; to contribute to global resource and waste constraints, and the solution of marine plastic problems making use of Japan's technology, innovation, and environmental infrastructure; and to create new growth sources such as economic growth and job creation through the development of resource recycling-related industries (MOEJ, 2019).

The strategy has six pillars (Reduce; Recycle; Recycled material and bioplastic; Measures for marine plastic; International collaboration/cooperation; and Developing basis for action) (Table 2.2) with several milestones as listed below to promote plastic resource circulation (MOEJ, 2019).

Milestones

- Twenty-five percent reduction of waste one-way plastic generation by 2030
- Achieve design for plastic packaging and containers to be recyclable and reusable by 2025
- Recycle, reuse, etc. covering 60% of plastic packaging by 2030
- One hundred percent effective utilisation of all used plastics by 2035
- Double the use of recycled plastic by 2030
- Increase domestic shipping of biomass plastic to two million tonnes/year by 2030

The Roadmap for Bioplastics Introduction was also formulated to support the achievement of the government's 2030 bioplastics target (MOEJ 2021).

Column: Plastic Flow in Japan

The Plastic Waste Management Institute publishes annual estimates on plastic recycling. According to the estimates (data for 2017), material recycling consists of about 23% of total waste treatment, chemical recycling about 4%, energy recovery about 58%, and incineration and landfill about 14%. Out of the 2.1 million tonnes of material recycling, about 0.62 million tonnes is used for recycled plastic input in Japan and the remaining amount is considered to be for export. It should be noted that exports decreased to about one million tonnes in 2018 from 1.5 million tonnes in 2017, probably due to the import restrictions in China and South-East Asia (Fig. 2.3).

2.2.5.2 Circular Economy Vision 2020

In May 2020, Ministry of the Economy Trade and Industry (METI) released its Circular Economy Vision (METI, 2020). While the 1999 version of the vision mainly emphasised transformation to the 3Rs, this 2020 version aims to strengthen the medium- and long-term competitiveness of Japanese industry by transitioning to CE, and seizing new business opportunities that will lead to a "virtuous cycle of environment and growth". The government intends to encourage voluntary actions by the private sector. It clearly states that the production and service industries should voluntarily design more circular products and services to create a circulating system that includes recycling and standardisation. It also points out that the key

Table 2.2 Pillars and major actions under the plastic resource circulation strategy

Pillars	Actions
Reduce	Reduction in the use of single-use plastics (such as compulsory plastic bag charge)
	Promoting alternatives for petroleum-originated plastics
Recycle	Clear and effective separation and recycling of plastic resources
	Strengthening on-land collection for fishing gear
	Minimising costs and maximising effective resource utilisation through collaboration and overall optimisation
	Establishment of a domestic resource recycling system responding to the import ban in Asia
	Fair and optimal recycling system that promotes innovation
Recycled material and bioplastic	Potential improvement (supporting technological innovation and infrastructure development)
	Demand stimulation (government initiative procurement (green purchasing), incentive measures, etc.)
	Handling of chemicals information for circulation use
	Biomass plastic use in designated bags for combustible waste
	Integrated introduction with bioplastic introduction roadmap and waste-related business management
Measures for marine plastic	Eradication of waste littering and illegal dumping, appropriate treatment
	Collection and treatment of beach drifting materials, etc.
	Capturing marine litter status (advancement of monitoring method)
	Microplastics spill control (such as reduction of microbeads in scrub products)
	Promote alternative products innovation
International collaboration/cooperation	Supporting developing countries to implement effective measures through international cooperation and business development by exporting Japanese infrastructure, technology, etc.
	Establishment of global monitoring and research network on marine plastic emissions, ecological impacts, standardisation of monitoring methods, etc.
Infrastructure development	Social system establishment (recycling infrastructure/supply chain development)
	Technology development (plastic substitution by renewable resources, innovative recycling technology, consumer lifestyle innovation)
	Surveys and research (actual use of microplastics, impact, outflow situation, measures to control outflow)
	Cooperation and collaboration (development of "plastic smart" campaign)
	Promotion of resource recycling-related industries
	Information infrastructure (ESG investment, ethical consumption)
	Infrastructure for overseas development

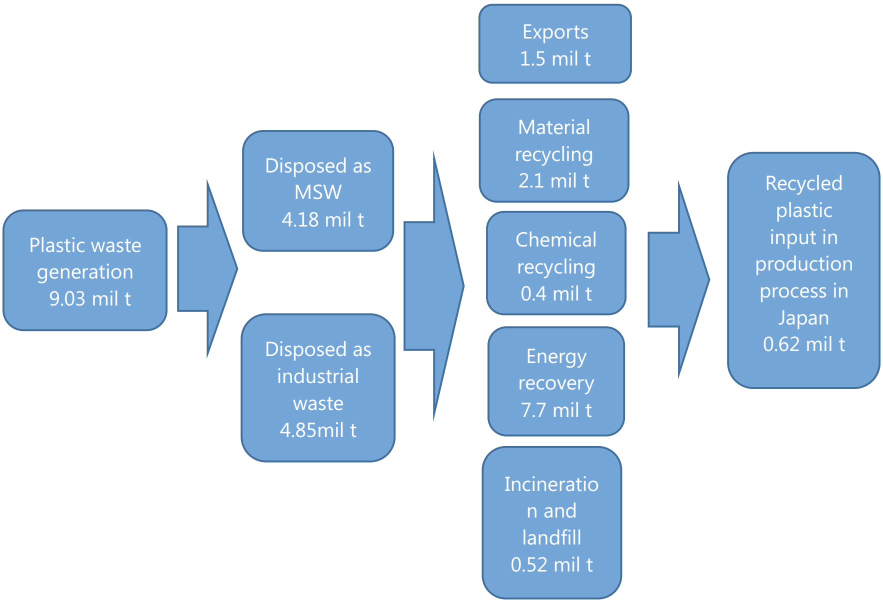


Fig. 2.3 Simplified waste plastic flow for year 2017. (Source: Authors based on the data provided by Plastic Waste Management Institute (Plastic waste management institute: Plastic recovery and recycle flow in 2017 (*Purasuchic saishigenka hurouzu*), https://www.pwmi.or.jp/pdf/panf2.pdf (Accessed Feb. 2023)))

drivers include digital technology, increasing demand from markets, and evaluation from society and investors for environmental action. Priority areas are listed as plastics, textiles, CFRP (carbon fibre reinforced plastic), batteries, and PV panels.

2.2.6 Public–Private Partnerships

Responding to the global momentum on plastic issues, public–private partnerships have been formulated and expanded on plastic issues. The following are major public–private partnership:

2.2.6.1 Plastics Smart campaign/Plastics Smart Forum[16]

"Plastics Smart—for Sustainable Ocean" is a campaign led by the Ministry of the Environment to support collaboration among individuals, local governments, NGOs, companies, and research institutions. The campaign intends to disseminate efforts to solve the global marine plastics problem through campaign sites and various events such as meetings, awards, and symposiums. Related to the campaign, the Plastics Smart Forum was established as a platform to promote dialogue and information

[16]Plastics Smart http://plastics-smart.env.go.jp/ (accessed Feb. 2023).

exchange between companies and organisations and to encourage a nationwide smart approach to plastics such as reducing unnecessary one-way (single-use) plastic discharge, and separation and collection to reduce marine plastics. As of 27 June, 329 organisations and companies had joined the forum.

2.2.6.2 Japan Clean Ocean Material Alliance (CLOMA)[17]

CLOMA was established in November 2018 supported by METI. The alliance aims to promote the development and introduction of revolutionary alternatives to plastics for sustainable use of plastic products and reduction of plastic waste as well as to accelerate innovation by promoting new approaches in the 3Rs and alternative materials that make more sustainable use of plastic products through public–private partnerships.

The alliance will engage in: (1) information-sharing between providers of raw materials and user companies through technological and business matching events and conveyance of information on leading case examples; (2) ascertaining the latest technical trends through technology exchange and technical seminars with research institutions; (3) collaboration with international organisations, overseas research institutes, and other associations as well as international collaboration to convey information to developing countries and other regions; and (4) encouraging companies in a variety of fields to collaborate in effective utilisation of plastic products in general.

2.2.6.3 Japan Partnership for Circular Economy (J4CE)[18]

The “Japan Partnership for Circular Economy (J4CE)” was founded in March 2021 by MOEJ, METI and Keidanren (Japan Business Federation), for the purpose of strengthening public and private partnerships, with the aim of further fostering understanding of the circular economy among a wide range of stakeholders, including domestic companies, and promoting initiatives in response to the accelerating global trend towards a circular economy.

One of the activities is to collect and share examples of advanced circular economy initiatives in Japan. As of June 2022, 148 Japanese companies and organisations participated the partnership, and 140 cases are posted on the website. “Noteworthy Cases” brochure, which introduced 28 cases among the 140 cases, was released in September 2021. On its website, several interesting cases are found such as retailors’ efforts to address plastic issues, product information (recycled plastic etc.) sharing with blockchain technology, business-to-business cooperation on plastic packaging recycle.

J4CE also organises “Public–Private Dialogue” events to exchange information and opinions among the public and business stakeholders.

[17] CLOMA https://cloma.net/english/(accessed Feb. 2023).

[18] J4CE https://j4ce.env.go.jp/en (accessed Feb. 2023).

2.3 Results and Discussion

In this section, quantitative data is presented for some of the basic parameters related to CE: waste generation and landfill site capacity, resource productivity, cyclical use rate, and the amount of final disposal.

2.3.1 Waste Generation

The generation of industrial and municipal waste in Japan reached a peak in 2000 and started to steadily decrease as a result of policy implementations. In fiscal 2018, the total amount of municipal waste discharged was 42.72 million tonnes, which amounts to 918 g per person per day. The amount of industrial waste discharged in recent years has been around 400 million tonnes (MOEJ 2020) (Fig. 2.4).

2.3.2 Resource Productivity

The resource productivity indicator in Japan is defined as Resource Productivity = GDP/DMI: Direct Material Input. Before FY2010, this indicator had been increasing substantially due to a reduction in public construction. It then stagnated for the next 5 years (until 2015), and resource productivity slowly started to grow again in the following years. Resource productivity in FY2015 was JPY 382,000/t, an increase of 58% compared to FY2000, and in FY2017 it was approximately JPY 393,000/tons, an increase of approximately 63% compared to FY2000. Japan is aiming for resource productivity of JPY 490,000/t in 2025 (approximately twice as much as the figure of about JPY 242,000/t in 2000) (MOEJ 2020) (Fig. 2.5).

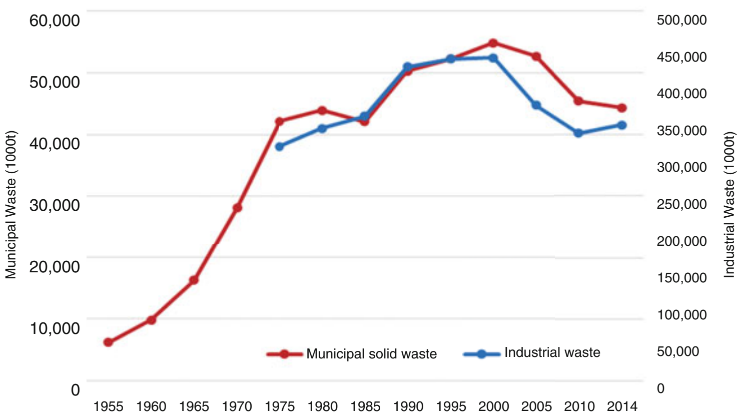


Fig. 2.4 Municipal and industrial waste generation in Japan (1000 t/year). (Source: Developed by authors based on MOEJ (2014) and Environment statistics by Ministry of the Environment, Japan)

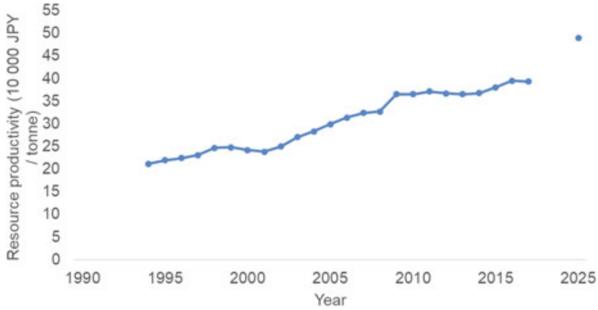


Fig. 2.5 Resource productivity in Japan. (Source: developed by authors based on MOEJ 2020)

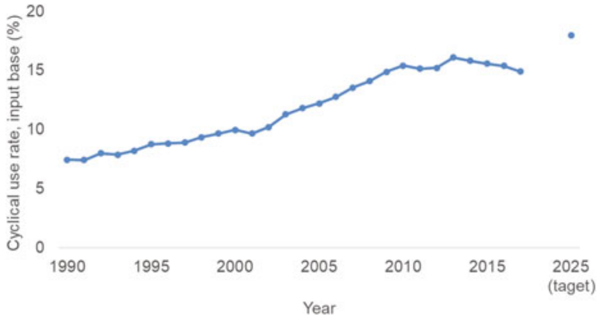


Fig. 2.6 Cyclical use rate (input) in Japan. (Source: developed by authors based on MOEJ 2020)

2.3.3 Cyclical Use Rate

Cyclical use rate (resource/input base) is defined as cyclical use rate = cyclical use amount/(cyclical use amount + DMI). The rate showed an increase until around 2010, with a particularly steep upward trend after 2000. This could be due to the increase in recycled materials driven by the formulation of SMCS. Compared to 2000, the cyclical use rate on the input side in 2017 increased by about five points to about 14.9%. However, since 2010, the rate has stagnated. The goal is to increase the cyclical use rate to 18% in 2025. If this goal is achieved, it would indicate an approximately 80% improvement compared to the year 2000, when the value was around 10% (MOEJ 2020) (Fig. 2.6).

Cyclical use rate (waste base) is defined as cyclical use amount/waste generation. The value was 43.3% in 2017, meaning that the cyclical use rate on the basis of waste increased by about seven points compared to the year 2000. Japan set a goal to increase this value to 47% in 2025, which is an approximate 20% improvement compared to 2000 (when value was about 36%) (MOEJ 2020) (Fig. 2.7).

2.3.4 Final Disposal Amount

The total final disposal amount is the sum of the direct final disposal amount and the final disposal amount after intermediate treatment. The final disposal amount

Fig. 2.7 Cyclical use rate, waste base (%) in Japan. (Source: developed by authors based on MOEJ 2020)

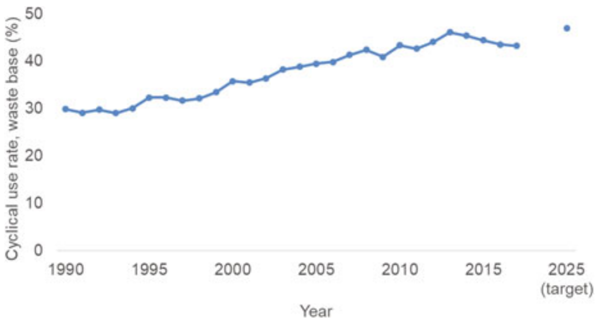
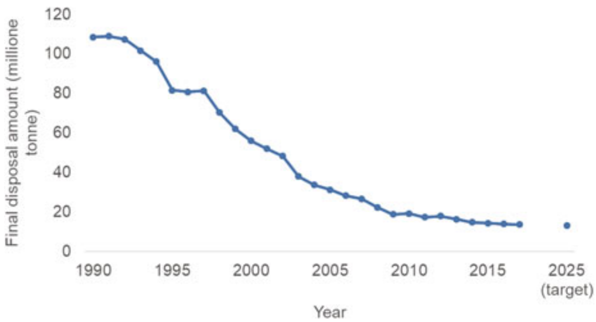


Fig. 2.8 Final disposal amount in Japan (Source: developed by authors based on MOEJ 2020)



dropped dramatically from 1990. However this downward turn has recently slowed down. In 2018, the total final disposal amount was 3.84 million tonnes, and the final disposal amount per person per day was 82g (MOEJ 2020) (Fig. 2.8).

2.4 Case Studies

2.4.1 City

2.4.1.1 Kitakyushu City

Kitakyushu City is an example of the cooperative strong will of the private and public sectors, to carry out the transition of a once extremely polluted city, to one of the most environmentally conscious cities in Japan. Kitakyushu is especially known for its sustainable solid waste management practices and for its advanced technologies that foster the circular economy.

Overall, households have the opportunity to separate waste into 15 types or 21 categories. For burnable waste, glass bottles and cans, PET bottles, and plastics other than PET bottles, households are obliged to purchase a designated garbage bag (each type has its own colour). The price set on the garbage bags played a significant role in motivating the citizens to decrease the generation of their household waste (Premakumara 2015). Paper and cardboard, plastic trays, as well as plasticised paper containers (such as those for milk and juices), and used cooking oil can also be collected separately and taken to designated collection stations. Citizens also practice separate collection of big and small electronic appliances, bulky garbage (such as furniture), small metal items, ink cartridges, batteries, and fluorescent lamps, which have to be collected at designated waste collection points.

Kitakyushu has three waste-to-energy incineration facilities to treat burnable household waste. The incinerators are equipped with pollution-preventing filters or wet scrubbers. The generated electricity provides energy to the incineration plants and nearby recycling facilities, while the surplus power is sold to the electric power company. The heat produced during the waste incineration is also utilised. The remaining ash is safely disposed of in landfill, while ash produced at one of the incinerators is even recycled using ash smelting equipment (Premakumara 2015).

Plastic waste is used in coke ovens in steel mills—plastic waste, free from iron, other impurities, and PVC, is used as coke, chemical feedstock, and fuel. Due to the lack of oxygen, the plastic waste does not combust inside the chamber, but it is cracked thermally at high temperatures. The yields of the process are (1) production of hydrocarbon oil that is used as chemical feedstock (40%), (2) coke, used as an iron ore reducing agent (20%), and (3) coke oven gas used for generating power (40%) (PWMI 2019). In 2019, 90% of plastic waste was used in the coke ovens, and 10% went for material recycling (JCPRA 2019).

Kitakyushu City promotes environmental activities in businesses and is devoted to the creation of awareness-raising programmes that educate citizens on sustainable activities, such as recycling, as well as city and beach clean-ups. The city also introduced the so-called Teitan points[19], designed to promote citizens "environmental activities (eco-activities)", and it promotes environmental learning for retirees and preschool children among others. To promote and reward green businesses in Kitakyushu, the city established the Eco-Premium programme, which gives awards for selected green products and services manufactured or provided within the city (City of Kitakyushu 2017). The city is highly aligned with the SDGs. Each year, Kitakyushu Urban Centre (IGES KUC) organises SDGs training on various topics related to the environment. The city recently released a CE roadmap named Kitakyushu Circular Economy Vision (KICS 2022). One of the projects proposed in the roadmap is the establishment of a so-called SDGs social farm. The farm will use compost from food waste to grow crops and employ technologies that keep resource efficiency at the highest level. Workers at the farm will be people with disabilities and elderly people, thus the farm will be adjusted to ease their work. Their mission is also to break the common opinion that farming is a low-status profession by inviting the younger generation to get involved in their agricultural program.

[19] https://www.city.kitakyushu.lg.jp/files/000814988.pdf

2.4.2 Digitalisation for Waste Management

The Japanese government has introduced a concept called Society 5.0 in which various social problems are solved by incorporating the innovations of the Fourth Industrial Revolution into all industries and throughout society (Cabinet Office 2016). The SMCS fundamental plan applies the concept to ensure resource circulation and achieve resource efficiency through digitalisation (MOEJ 2018a). This can have a radical impact on the development of innovative green technologies and practices. The tools of Society 5.0 will provide great opportunities in the area of product design (DfE, design for the environment, SDG 9), as well as in the area of material circulation (SDG 12), and wider also one increased societal well-being (Cabinet Office 2016). Seeds have already been planted—for material circulation improvement, one of such is the establishment of a Japanese IoT Council of waste management and recycling (IoT-Recycle 2021). As of January 2021, the Council consists of 65 public and private institutions. The council aims to discuss and promote IoT in the waste management and recycling industry, based on industry–academia–government collaboration (aligned with the SDG 17—partnership for goals). The utilisation of IoT has the ability to reform waste management practices by improving logistical efficiency, establishing automation of waste sorting, disassembling, recycling, and upgrading disposal systems such as incineration plants. This will result in higher efficiency of the operation processes and decrease the need for labour. A scheme on AI, big data with information on design, raw material, usage, location of collection, transportation final disposal, storage of recycle materials as well as operating and power generation of incineration for efficient and optimised of recycling and waste management has been explored with various stakeholders (IoT-Recycling 2021).

2.5 Opportunities, Challenges, and Prospects

Stagnating recycling rates, cyclical use rates, and resource productivity indicate that there is plenty of room for improvement. Expansion of the targets set out in recycling legislation could help to increase the recycling rates. This would require encouraging collaboration to form further linkages between the manufacturing sector, the waste management sector as well as the social system. There is also a gap in demand and supply for secondary resources. Motivating the demand for secondary resources is also key in Japan. This could be achieved through quality control of recycled materials, regulations, or incentive mechanisms to use secondary materials or some other policy instrument to make the use of secondary material easier and contribute to any cost reduction measures/technologies in the recycling sector. Additionally, as Japanese resource circulation depends on exports to Asia to some extent, further promotion of domestic high value-added recycling business/technology should be promoted. New approaches for international resource circulation are needed, bearing in mind the industrial structure changes in the manufacturing sector.

Additional opportunities lie in application of remanufacturing, refurbishment, repair, and direct reuse (RRRDR) and in offering products and mobility as a service (PaaS and MaaS) as well as sharing businesses, instead of products for purchasing. In light of these aspects, active engagement of the ICT sector is expected to improve access to a wider range of circular economy businesses and products.

To address industrial transformation for circular economy transition, especially for waste management sector, SMEs or even smaller sized companies which are major players in the circular economy have to overcome various challenges. They have faced a lack of human resources and strong competition within sectors (MOEJ 2017b). To increase the quality of recycling and further promote CE in Japan, there needs to be more collaboration in the waste management sector as well as cooperation between the manufacturing and waste management sectors. Some structural transformations in the business model and social system would be needed with the support of elaborated institutional re-arrangement.

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Nevertheless, Japanese society has gradually started to shift from waste management to further promotion of SMCS and a more ambitious CE. Various consumer and associated business actions indicate increased serious recognition on the circular economy relevant to the international dynamism on CE including plastic and climate neutrality. With the fourth SMCS plan, the plastic resource circulation strategy by the Ministry of the Environment as well as the circular economy vision by the Ministry of the Economy, Trade and Industry, the Japanese government has promoted several projects to create innovation on CE in the fields of business and technology. More technologies and systems are set to be created in the near future. The government is also considering contributions to the circular economy as climate change mitigation in projects. More discussion from the perspective of a whole lifecycle environmental impact relating to sustainable circularity would therefore be needed.

2.6 Conclusions

This chapter provides an overview of policies and practices for the circular economy in Japan. The Japanese government has taken significant steps to develop a CE policy framework, incorporating the Japanese concepts of SMCS and the 3Rs to promote waste minimisation and effective utilisation of resources. As a result of the rapidly growing economy, Japan faced changes in production and consumption patterns which led to increased consumption and waste generation. National policy development was driven by a concern about the lack of landfill sites and the need for effective resource use.

In light of this, a very finely tuned SMCS policy framework with some supporting tools and programmes such as labelling and eco-towns has been formulated. Japanese stakeholders have carried out a wide range of actions and introduced elemental technologies for CE to respond to and go beyond the requirements of SMCS policies, including the expansion of separation, recycling and waste management efforts by citizens and businesses, as well as promoting design for the environment. Local governments have set a large number of separation categories depending on the capacity of their waste management facilities. These efforts have resulted in a reduction in waste generation, extension of the life of landfill sites, and increased resource productivity.

While there is still room for improvement, Japan has set ambitious plans for the transition to CE using established policy tools, initiatives that promote practising CE in businesses, application of advanced technology and digitalisation, as well as developing and implementing a comprehensive regional-CES concept in several regions. For successful implementation of the above measures, multi-stakeholder discussions must continue to take place from the perspective of transition with long-term vision.

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3 The Pathway Toward Circular Economic Development in China: Policies, Case Studies, and the Role of Universities

Zhe Liu and Raymond P. Cote

Abstract

With the opening of China to international trade and its economic reforms, China has achieved significant progress in terms of its economic development in the past 40 years. However, a number of serious environmental challenges have emerged such as massive waste generation, resource depletion, frequent environmental events involving hazardous materials, and copious emissions of greenhouse gas emissions, which have posed serious threats to the wellbeing of the people as well as natural ecosystems. In recognition of this rapidly evolving situation, China began to pursue a unique pathway toward sustainable development goals by means of circular economic development (CED) in the early twenty-first century. Through the past 20 years, China has emerged as one of the world leaders in the field of CED. In this chapter, some of the key policies, strategies, and measures in promoting CED are introduced. Applied practices of CED such as industrial symbiosis, eco-industrial parks, and circular economy industrial parks initiated in China are highlighted. Co-benefits in terms of economic development, carbon emission reductions, and promoting resource productivity achieved by CED at the scale of individual industries as well as industrial clusters in China are also demonstrated. In addition, the particular roles of research and education at Chinese universities in advancing CED in China are explored with emphasis on

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case studies. With the dynamic development toward CED in China, some conclusions are drawn and directions for the future are recommended.

Keywords

Circular development · Policies · Research and teaching · Co-benefits · China

3.1 Introduction

A circular economy (CE) is defined as an economic system in which products are designed as "restorative and regenerative with the goal of utilizing products at the highest value at all times, distinguishing between the technical and biological aspects of the cycles" (Ellen MacArthur Foundation 2016a, b). Circular economic development (CED) stems from the 3R principle (reduce, reuse, and recycle). With the increasing awareness across the globe, the CED model is considered by the United Nations as one of the most important approaches for achieving sustainable development goals (SDGs) for humanity and the planet (UN Environment 2018a, b). In China, in order to pursue a pathway toward SDGs, the Chinese government promoted "ecological civilization" as a national strategy in 2017. CED along with other strategies such as low carbon development and green development are considered complementary pillars to implement the national "ecological civilization" and achieve sustainable development.

CED has largely been implemented in the following three ways: First, waste and by-products are identified, exchanged, and reutilized among various kinds of enterprises within an industrial cluster such as eco-industrial parks (EIPs). Second, industrial waste and municipal waste are reutilized and recovered at the scales of enterprises, industrial parks, and even communities through industrial symbiosis and urban symbiosis. Third, CED is implemented within a specific industry such as the steel industry, cement industry, or plastics industry by recovering and reutilizing by-products and waste. Taking eco-industrial park construction for example, in 2001, China initiated the first eco-industrial pilot project in Guangxi province namely Guigang industrial park, which is an industrial park anchored by the sugar industry. Among the industries in this park, a number of symbiotic linkages have been successfully implemented.

In the past 20 years, China has initiated more than 200 national-level EIPs pilot projects, among which dozens of industrial parks have met the national standard for EIPs. It must be clarified that the nature of EIPs in practice in China is different from the original concept of EIPs proposed by the academic world. From the theoretical perspective, the concept of the industrial parks as an ecosystem was advanced by Cote and Hall in 1995 (Cote and Hall 1995), and was defined later by the US President's Council on Sustainable Development (USAPCSD) (1996) as "a community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and the local habitat) leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community" (USAPCSD 1996). The theoretical features of an EIP should include: integrating ecological capacity into planning decisions; maximizing the use of renewable energy; green buildings design; selecting industrial tenants based in part on their compatibility for symbiosis with other tenants; business "webs" that involve producers and consumers, scavengers and decomposers; material redundancy within the structure of the system; water and wastewater infrastructure that allows recovery and reuse; and information management systems which facilitate networking (Cote and Smolenaars 1997; Cote and Cohen-Rosenthal 1998; Cote 1998, 1999; Geng and Cote 2002). In practice, when an industrial park has passed the corresponding standard for EIPs set by the authority, in China, it can be promoted as an EIP (see Table 3.2).

In the past 20 years, China has expanded from initiating the first eco-industrial pilot project to adopting a circular economic promotion law, establishing circular economy industrial parks and expanding to broader circular projects. Thus, this chapter will explore the key policies, laws, and strategies which China has adopted to implement its "ecological civilization" (see Table 3.1). As can be seen in Table 3.1, efforts to foster a CE in China have been spread throughout the government. There is an extensive support system for the establishment of a CE. The benefits of CED in China are not yet clear but are being analyzed through selected case studies. In addition, teaching and research in academia in the field of CED have been playing an important role in advancing CED in China. This chapter will also review the role of universities in the past 20 years.

3.2 CED Progress in China

3.2.1 Eco-Industrial Parks (EIPs)

The Ministry of Ecology and Environment (MEE) initiated the first eco-industrial pilot project namely Guigang industrial park in Guangxi province in 2001. Guigang industrial park is an industrial cluster anchored by sugar industries. The industrial symbiosis network in Guigang industrial park includes the paper industry, wood industry, and alcohol industry, which were established around the sugar industries. The Group responsible for these industries had successfully implemented a number of symbioses. Following this initiative, in order to facilitate EIP construction nationally, MEE released a preliminary standard which would have to be satisfied if an industrial park was to be designated a national EIP in 2006. The standard system included the four main indicators namely economic development, material reduction and circulation, pollution control, and industrial park management respectively. In 2009, MEE formally released the national standard for EIPs, the only country to do so. In 2015, the MEE updated the national standard system for EIPs. The main difference between the updated system and the previous one is that two key indicators were included in the new standard system namely industrial symbiosis and information disclosure as can be seen in Table 3.2.

Table 3.1 The policies associated with circular economy in China

Order	Law, policy or guideline	Release date	Responsible agency
1	Planning policy guideline of circular economic pilot industrial park	2003.12	The Ministry of Ecology and Environment
2	The instructional views on development of circular economy	2005.7.2	The State Council
3	The notice of requirements for the compilation of pilot implementation plans of circular economy	2005.11.4	The National Development and Reform Commission
4	The designation of venous industry-based eco-industrial Parks	2006.9	The Ministry of Ecology and Environment
5	The notice of evaluation index system of circular economy	2007.6.27	The National Development and Reform Commission; The Ministry of Ecology and Environment
6	The Circular Economy Promotion Law of the People's Republic of China	2009.1	The Standing Committee of the National People's Congress
7	The guiding suggestion of the awarding pilot projects for circular economy	2009.6	The Standardization Administration
8	The first regional plan of recycling economy	2009.12.24	The State Development and Reform Commission; The People's Government of Gansu Province
9	Guidance on investment and financing support policy for circular economy	2010.4.19	The National Development and Reform Commission; The People's Bank of China; The China Banking Regulatory Commission; The China Securities Regulatory Commission
10	Guidance on promoting remanufacturing industry	2010.5.13	The National Development and Reform Commission; The Ministry of Science and Technology; The Ministry of Industry and Information Technology
11	The guidelines of development of circulatory economy	2010.12.31	The National Development and Reform Commission
12	The implementation plan for recycling economy development special fund to support resource utilization and harmless treatment of kitchen waste in pilot cities	2011.5.17	The National Development and Reform Commission; The Ministry of Finance

(continued)

Table 3.1 (continued)

Order	Law, policy or guideline	Release date	Responsible agency
13	Guidance on transformation of eco-industrial park based on circular economy	2012.3.21	The National Development and Reform Commission; The Ministry of Finance
14	The catalog of technologies and equipment	2012.6.7	The National Development and Reform Commission; The Ministry of Science and Technology; The Ministry of Ecology and Environment
15	The provisional rules for the management of special funds for development of circular economy	2012.7.20	The National Development and Reform Commission; The Ministry of Finance
16	The 12th 5-year plan for recycling economy development	2012.12.12	The State Council
17	The development strategy and immediate action plan of circular economy	2013.2.6	The State Council
19	The promotion plan for the circular economy	2015.4.14	The National Development and Reform Commission
20	Guidance for developing agriculture cycling economy	2016.2.1	The National Development and Reform Commission; The Ministry of Agriculture and Rural Affairs; The State Forestry Administration
21	The industrial green development plan (2016–2020)	2016.6	The Ministry of Industry and Information Technology
22	China's typical model for circular economy pilot projects	2016.6	The State Development and Reform Commission; Ministry of Finance
23	The evaluation index system for recycling Economy development (2017)	2016.12.27	The National Development and Reform Commission; The Ministry of Finance; The Ministry of Ecology and Environment; The National Bureau of Statistics of China
24	The leading program of circular economy	2017.4.21	The National Development and Reform Commission
25	The notice on efforts to accomplish green circular consumption	2018.4.27	The Ministry of Commerce
26	The notice of promoting the construction resources recycling base	2018.5.7	The National Development and Reform Commission; The Ministry of Housing and Urban-Rural Development of China
27	The guidelines for development of circulatory economy	2018.12.29	The State Council

(continued)

Table 3.1 (continued)

Order	Law, policy or guideline	Release date	Responsible agency
28	The promotion of comprehensive utilization of solid discarded objects in industrial clusters	2019.1.14	The National Development and Reform Commission; The Ministry of Industry and Information Technology
29	The development of industrial energy saving and green development	2019.4.1	The Ministry of Industry and Information Technology; China Development Bank
30	The guidelines for pilot implementation plan of "zero waste cities" construction and the index system of "zero waste cities"	2019.5.13	The Ministry of Ecology and Environment
31	The guideline to accelerate the development of a green and low-carbon circular economic development system	2021.2.22	The State Council

Source from: SEPA (2005), NDRC (2005, 2010a, b, c, 2011a, b, c, 2012b, c, d, e, 2015, 2016a, b, c, 2017a, b, 2018, 2019), The State Council (2006a, b, 2009, 2013, 2021), NPC (2008), SAC (2009), Ministry of Commerce (2018), Chinese Government (2018), Ministry of Industry and Information Technology (2019), MEE (2019a, b)

The development of EIPs has been mainly attributed to governmental direction. In this regard, MEE released a series of policies advancing EIPs in China (see Table 3.3). The national and provincial governments have applied financial tools such as tax policy to direct local industrial parks encouraging the transition toward EIPs and green industrial parks. In the past 20 years, China has achieved significant progress in this program. So far, more than 200 EIPs pilot projects have been initiated by MEE across the nation, including which dozens of pilot projects have met the national standard for EIPs and become national demonstration EIPs in China.

3.2.2 Circular Economy Industrial Parks

The National Development and Reform Commission (NDRC) in China is in charge of initiating the program of circular economy industrial parks. As can be seen in Table 3.4, a number of policies were released for advancing the development of circular economy industrial parks in China. In 2010, the NDRC issued a document for promoting CED titled "The notice regarding the policy for financial support of CE projects". The notice required that local governments should implement the relevant policies and measures to promote CED at the scale of enterprises, industrial parks, and the community. The notice also encouraged industrial parks to carry out innovative measures for advancing infrastructure establishment for implementing the recycling of waste water and garbage. Apart from this regard, the notice required

Table 3.2 Standards for Chinese eco-industrial parks as updated in 2015

Item	No.	Indicator
Economic development	1	The proportion to high-tech enterprises output value of gross industrial output value
	2	Per-capita industrial added value (IAV)
	3	The average 3-year growth rate of industrial added value
	4	The proportion to remanufacturing industry added value of the gross industrial added value
Industrial symbiosis	5	Number of eco-industrial chains added
	6	Utilization rate of industrial solid waste
	7	Recycling rate of renewable resources
Resource conservation	8	Industrial added value of unit industrial land area
	9	The average 3-year annual growth rate of industrial added value per unit of industrial land area
	10	Efficiency of comprehensive energy consumption
	11	Energy consumption per unit of industrial added value
	12	Application ratio of renewable energy
	13	Efficiency of fresh water consumption
	14	Fresh water consumption per unit industrial added value
	15	Recycling rate of industrial water
	16	Reuse rate of reclaimed water
Environmental protection	17	Rate of reaching the discharging standard for key pollution sources
	18	Key pollutant emissions
	19	Frequency of severe environmental accidents
	20	Degree of Completion of environmental management system strategies
	21	Implementation rate of key enterprises' clean production audit systems
	22	Centralized sewage treatment facilities
	23	The completion rate of environmental risk prevention and control system
	24	Utilization rate of industrial solid waste(including hazardous wastes)
	25	Efficiency of main pollutant emissions
	26	The annual reduction rate of carbon dioxide emissions per unit of industrial added value
	27	Waste water emissions per unit industrial added value
	28	Solid waste discharge per unit of industrial added value
	29	Green cover percentage
Information disclosure	30	Environmental information disclosure rate of key enterprises
	31	Degree of completion of the ecological industry information platform
	32	Number of Eco-industry publicity campaigns

Table 3.3 Policies associated with eco-industrial parks in China

Number	Periods	Year	Title of policy document	Issuing agency
1	The first stage: pilot and exploration stage (2000–2006)	2000	Four industrial parks in Quzhou, Zhejiang Province carried out the planning and exploration of ecological industrial parks	
2		2001	Guigang, Guangxi and Nanhai, Guangdong were approved by the environmental protection department as eco-industrial construction demonstration parks	
3		2003/12/31	Provisions for the Application, Naming, and Management of the National Eco-Industrial Demonstration Parks (For Trial Implementation)	Ministry of Ecology and Environment (formerly State Environmental Protection Administration)
			Annex 1. Provisions on Application, Naming, and Management of the National Eco-Industrial Demonstration Parks (For Trial Implementation)	
			Annex 2. Planning Guides for Eco-industrial Demonstration Parks (For Trial Implementation)	
			Annex 3. Provisions on Application, Naming, and Management of Circular Economy Demonstration Zone (For Trial Implementation)	
			Annex 4. Planning Guides for Circular Economy Demonstration Zones (For Trial Implementation)	
4		2006/6/2	Announcement on Issuing Three National Environmental Protection Industry Standards, such as Industry Eco-Industrial Parks Standards (For Trial Implementation)	Ministry of Ecology and Environment (formerly State Environmental Protection Administration)
			Annex 1. Standards for Industrial Eco-Industrial Parks (For Trial	

(continued)

Table 3.3 (continued)

Number	Periods	Year	Title of policy document	Issuing agency
			Implementation) (HJ/T 273-2006)	
			Annex 2. Standards for Comprehensive Eco-Industrial Parks (For Trial Implementation) (HJ/T 274-2006)	
			Annex 3. Standards for Venous Industry Eco-Industrial Parks (For Trial Implementation) (HJ/T 275-2006)	
5	The second stage: The stage of management refinement (2007–2010)	2007/ 4/3	The Construction of National Eco-Industrial Demonstration Parks	Ministry of Ecology and Environment (formerly s
6		2007/ 12/19	The Measures for the Application, Naming, and Management of the National Eco-Industrial Demonstration Parks (For Trial Implementation)	Ministry of Ecology and Environment (formerly State Environmental Protection Administration); Ministry of Commerce; Ministry of Science and Technology
7		2007/ 12/24	Announcement on the National Environmental Protection Industry Standards "Guidelines for the Compilation of Eco-Industrial Park Construction Planning"	Ministry of Ecology and Environment (formerly State Environmental Protection Administration)
8		2008/ 7/7	The Materials for the Conference on the Construction of the National Eco-Industrial Demonstration Parks	The General Office of Ministry of Ecology and Environment (formerly the General Office of Ministry of Environmental Protection)
9		2009/ 6/23	Announcement on Issuing the National Environmental Protection Standards "Standards for Comprehensive Eco-Industrial Parks"	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection)
10		2009/ 12/21	Strengthening the Development of Low-carbon Economy in National	The General Office of Ministry of Ecology and Environment (formerly the General

(continued)

Table 3.3 (continued)

Number	Periods	Year	Title of policy document	Issuing agency
			Eco-Industrial Demonstration Parks	Office of Ministry of Environmental Protection)
11	The third stage: the stage of perfecting standards and regulations (2011–2015)	2011/11/2	Letter on Soliciting Opinions for the Guidance for Improvement of the Construction of National Eco-Industrial Demonstration Parks (Draft for Comments)	The General Office of Ministry of Ecology and Environment (formerly the General Office of Ministry of Environmental Protection)
12		2011/12/5	Guidance on Strengthening the Construction of National Eco-Industrial Demonstration Parks	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection); Ministry of Commerce; Ministry of Science and Technology
13		2012/8/6	Announcement on the Revision Scheme of Standards for Comprehensive Eco-Industrial Parks (HJ274-2009)	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection)
14		2013/2/6	Circular on approving Shanghai Chemical Industry Economic and Technological Development Zone, Shandong Yanggu Xiangguang Eco-Industrial Park and Linyi Economic and Technological Development Zone as National Eco-Industrial Demonstration Parks	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection); Ministry of Commerce; Ministry of Science and Technology
15		2015/12/17	The Measures for the Administration of National Eco-Industrial Demonstration Parks	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection); Ministry of Commerce; Ministry of Science and Technology
16		2015/12/24	Announcement on the National Environmental Protection Standards "Standard for National Eco-Industrial Demonstration Parks"	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection)

(continued)

Table 3.3 (continued)

Number	Periods	Year	Title of policy document	Issuing agency
17	The fourth stage: The normal operation stage (2016–)	2017/8/8	Carrying Out Self-Examination of Environmental Protection in National Eco-Industrial Demonstration Parks	Ministry of Ecology and Environment (formerly Ministry of Environmental Protection); Ministry of Science and Technology
18		2018-3-12	Submitting Evaluation Report on the Construction of National Eco-Industrial Demonstration Parks in 2017	Department of Science and Technology Standards of Ministry of Ecology and Environment (formerly Department of Science and Technology Standards of Ministry of Environmental Protection)
19		2019/5/28	Guidance on Promoting Innovation in State-level Economic and Technological Development Zones and Building New Highlands of Reform and Opening Up	The State Council
20		2019/6/26	Carrying out the Review and Evaluation of the National Eco-Industrial Demonstration Parks in 2019	The General Office of Ministry of Ecological Environment; The General Office of Ministry of Commerce; The General Office of Ministry of Science and Technology
21		2020/12/21	Approving Wuhu Economic and Technological Development Zone and Other 10 Parks as National Eco-Industrial Demonstration Parks	Ministry of Ecological Environment; Ministry of Commerce; Ministry of Science and Technology

Source from Jin et al. (2003), Shi and Wang (2010), MEE (2003, 2006, 2007a, b, c, 2008, 2009a, b, 2011a, b, 2012, 2013, 2015a, b, 2017, 2018, 2019a, b, 2020)

Table 3.4 The policies associated with circular economy industrial parks released by Chinese governments

Order	File name	Releasing date	Issuing agency
1	Designation of the first group of pilot projects for circular economy	2005.11.01	The State Council; The National Development and Reform Commission; The Ministry of Ecology and Environment; The Ministry of Science and Technology; The Ministry of Finance; The Ministry of Commerce; National Bureau of Statistics
2	The 12th 5-year plan for recycling economy development	2006.8.24	The State Council
3	Resource-saving and environment-friendly society construction in 2005 and the key works in 2006	2016.3.13	The Department of Resource Conservation and Environmental Protection of the Development and Reform Commission
4	The National Conference of pilot projects for circular economy	2007.11.30	The National Development and Reform Commission; The Ministry of Ecology and Environment
5	Guidance of the second group of pilot projects for circular economy	2007.12.13	The State Council; The National Development and Reform Commission; The Ministry of Ecology and Environment; The Ministry of Science and Technology; The Ministry of Finance; The Ministry of Commerce; The National Bureau of Statistics of China
6	Launching the first group of demonstration projects of mining cities	2010.5.12	The National Development and Reform Commission; The Ministry of Finance
7	Launching the second group of demonstration projects of mining cities	2011.10.17	The National Development and Reform Commission; Ministry of Finance
8	Guidance on promoting the circular transformation of the Industrial Parks	2012.3.21	The National Development and Reform Commission; The Ministry of Finance
9	Launching the third group of demonstration projects of mining cities	2012.7.30	The Ministry of Finance
10	Launching the fourth group of demonstration base of mining cities	2013.9	The National Development and Reform Commission; Ministry of Finance
11	Launching the fifth group of demonstration base of mining cities	2014.7.22	The Department of Resource Conservation and Environmental Protection of the Development and Reform Commission; The

(continued)

Table 3.4 (continued)

Order	File name	Releasing date	Issuing agency
			Department of Economic Construction, The Ministry of Finance
12	The priority pilot projects of the circular economy	2015.6.25	The National Development and Reform Commission
13	Guidance on developing the agriculture cycling economy	2016.2.1	The National Development and Reform Commission; The Ministry of Agriculture and Rural Affairs; The State Forestry Bureau
14	Launching the first group of the national urbanization pilot projects	2018.5.4	The National Development and Reform Commission
15	The implementation plan of resource recycling base of 50 units including Chengdu Chang'an vein Industrial Park	2018.10.10	The National Development and Reform Commission; The Ministry of Housing and Urban-Rural Development
16	The acceptance result of the transformation of eco-industrial park based on circular economy and the construction of demonstration base of mining cities in 2019	2019.4.16	The National Development and Reform Commission; The Ministry of Finance
17	The acceptance result of the transformation of eco-industrial park based on circular economy and the construction of demonstration sites of mining cities in 2020	2020.10.14	The National Development and Reform Commission; The Department of Resource Conservation and Environmental Protection of the Development and Reform Commission; The Department of Economic Construction; The Ministry of Finance

Source from: The State Council (2005, 2006a, b), NDRC (2007a, b, 2010a, b, c, 2011a, b, c, 2012a, 2015, 2018), Ministry of Finance (2012, 2013)

the local administration to implement innovative administration measures to promote technological advancement for CED. The goal of this document was to achieve micro scale of waste circulation among enterprise, mid-scale of waste circulation at the scale of industrial parks, and even macro scale CED throughout the society.

China promulgated the national "Circular Economy Promotion Law" in 2008 and the law took effect in 2009. This law recognizes the activities associated with waste reducing, reusing, and recycling during the process of production, transformation, and consumption. The "Circular Economy Promotion Law" indicates that all sorts of industrial parks should organize the relevant enterprises to efficiently make use of resources. In addition, in the 12th national 5-year plan, transformation of industrial parks to circular economy industrial parks has been identified. As a result, industrial parks such as economic and technology development areas, and high-tech

Table 3.5 Standards for Chinese circular economy industrial parks released in 2005

Item	No.	Indicator
Resource generation	1	Major mine generation ratio
	2	Energy generation ratio
	3	Land generation ratio
	4	Water resource generation ratio
Resource consumption	5	Energy consumption per gross production
	6	Fresh water utilization per gross production
	7	Key product per energy consumption
	8	Key product per fresh water consumption
Resource utilization	9	Comprehensive use ratio of industrial solid waste
	10	Recycled ratio of industrial water
Waste emission	11	Industrial solid waste generation and recovery
	12	Industrial waste water emission
	13	SO_2 emission
	14	COD emission

industrial parks must make plans for the transition from the traditional industrial parks to parks based on the 3R principle to promote resource utilization efficiency and will have to achieve the goal of zero waste emission and sustainable development in future. The industrial resource recovery zone is a specific type of industrial park, in which the enterprises are dedicated to transforming wastes into industrial products in China designated by the authorities. For instance, the enterprises involved in PET resource recovery are making their cloth products from recovered PET plastic bottles waste. There are 48 such parks across the country,

In addition, of particular significance, NDRC released national circular economy industrial park indicators (see Table 3.5) in 2005 in order to further promote waste recirculation at the industrial park level, leading to 33 industrial parks being approved as national circular economy demonstration industrial parks (Geng et al. 2012). Compared to the national standard for EIPs, the indicator system for circular economy industrial parks has emphasized resource utilization efficiency. The NDRC advanced this initiative by working with academic experts providing guidance as well as consultation with the enterprises.

3.3 The Role of Universities

3.3.1 Teaching IE and CE

Teaching students is viewed as key to support CED in China in the future. In order to develop CED talents, industrial ecology (IE) courses were first introduced in Chinese universities in the early 2000s. Some key universities, including Tsinghua University, Dalian University of Technology (DUT), Northeast University, and Wuhan University began to offer one or more courses in IE to their students at

Table 3.6 Universities teaching industrial ecology

Order	University
1	Tsinghua University
2	Harbin Institute of Technology
3	Beijing Normal University
4	Northeastern University
5	Dalian University of Technology
6	Nanjing University
7	Fudan University
8	University of Science and technology Beijing
9	Sichuan University
10	Southeastern University
11	Chongqing University
12	Yunnan University
13	Jilin University
14	Shanxi University
15	Jinan University
16	Shanghai Polytechnic University

both the undergraduate and the graduate levels (Geng et al. 2009). In 2004, with support from the Luce Foundation, a first workshop on IE was jointly held in China by Tsinghua University and Yale University from the United States. More than 40 participants from 20 universities in China took part in the workshop. Since then, more universities have offered courses in IE (see Table 3.6). The IE courses are always taught by the School for Environmental Science and Engineering, School for Resource and Environment, or School for Environment and Ecology in the universities.

In addition to IE classes offered in Chinese universities, another course related to CED entitled "Resource Circulation Science and Engineering" has also been added to the curriculum in a larger number of universities in the past few years (see Table 3.7). These courses provide a theoretical and technical perspective on CED, with an emphasis on resource utilization efficiency.

As can be seen in Table 3.7, CE is largely taught from a scientific and technical perspective. In addition, Chinese scholars are increasingly playing an important role in advancing CED within the country. The scholars are involved in various activities with regard to CED such as advice on policy making, plan design or even conducting specific CE project reviews. Researchers also play an important role in technical guidance, and, in particular, they conduct research on case studies.

Table 3.7 Universities teaching courses in circular economy

Order	University
1	Beijing University of Technology
2	Tianjin University of Technology
3	Shanxi University
4	Northeastern University
5	Changchun University of Technology
6	Qiqihar University
7	Anhui University of Technology
8	Fuzhou University
9	Nanchang University
10	Shandong University of Technology
11	Wuhan Textile University
12	Neijiang Normal University
13	Yunnan Normal University
14	Qinghai Normal University
15	Shangluo University
16	Cangzhou Jiaotong College
17	Nankai University
18	North China University of Water Resources and Electric Power
19	Dalian University of Technology
20	Shenyang University of Chemical Technology
21	Jilin Institute of Chemical Technology
22	East China University of Science and Technology
23	Anhui University of Science and Technology
24	Fujian Normal University
25	Shandong University
26	Shandong Agricultural University
27	Hunan Normal University
28	Kunming University of Technology
29	Xi'an University of Architecture and Technology
30	Luoyang Institute of Science and Technology
31	Jiangsu University of Technology
32	Moutai Institute
33	Beijing University of Technology

3.3.2 Researching CE in China

3.3.2.1 Multi-Sectoral Case Studies

The national government identified economic and technology development zones (industrial parks) as a key strategy for stimulating economic development across the country in the early 1980s. In particular, these zones have comprehensive advantages on attracting foreign investment, improving technological abilities, and concentrating industrial activities through appropriate zoning. Through nearly

Table 3.8 Some case studies described in journals on IE and CE in China

Order	Name of industrial parks	Location
1	Tianjin Economic and Technological Development Area (TEDA)	Tianjin City
2	Guigang industrial park	Guangxi Province
3	Dalian Economic Development Area (DEDA)	Liaoning Province
4	Shenyang Economic Technological Development Area (SETDA)	Liaoning Province
5	Suzhou Industrial Park	Jiangsu Province
6	Beijing Economic-Technological Development Area (BETDA)	Beijing City
7	Guiyang EIP	Guizhou Province
8	Nanchang EIP	Jiangxi Province
9	Wuhu EIP	Anhui Province

30 years of development, industrial parks have substantially contributed to national economic development, leading to national economic transformation with higher economic efficiency. For instance, as early as 2011, nationally rated industrial parks had a gross domestic production (GDP) with a value of 47 million US dollars per square kilometer, 59 times higher than the national average level and 7.9 times higher than the average level of 36 major cities. The overall contribution of various industrial parks to the national economy would amount to about 60% of the total (Liu et al. 2015). However, challenges remained, such as excessive resource consumption and repeated cycles of construction, as well as the need to mitigate waste generation and the concomitant effects of environmental pollution. Therefore, industrial parks were identified as sites for demonstration projects for advancing CED in China. EIPs have been the focus of numerous case studies (see Table 3.8) for verifying various theories, methodologies, technologies, and policy implications. The general research directions have been associated with resource circulation, environmental emissions, or occasionally a broader perspective, for instance, of sustainability associated with economic, ecological, and resource systems. In this regard, studies of the implementation of CED strategies in the scale of industrial parks indicate that CED strategies can bring about co-benefits in terms of resource conservation, economic development, and environmental emission reductions (Liu et al. 2018a).

One particular case which has been studied by researchers is Tianjin Economic and Technological Development Area (TEDA) in promoting EIP and CED in China. TEDA case is arguably the most cited case studies in the field of CED in China (Geng and Zhao 2009; Liu et al. 2016a, 2018c). TEDA, founded in 1984, is one of the first national industrial parks in China. TEDA is a special development zone located on Bohai Bay in North China, in the east of the city of Tianjin. TEDA is a very large area comprised of eight districts (see Fig. 3.1). With rapid economic development and a low level of public's environmental awareness, environmental issues were beginning to limit further foreign investment. In order to improve the situation, TEDA adopted various strategies. One of the strategies identified was CED.

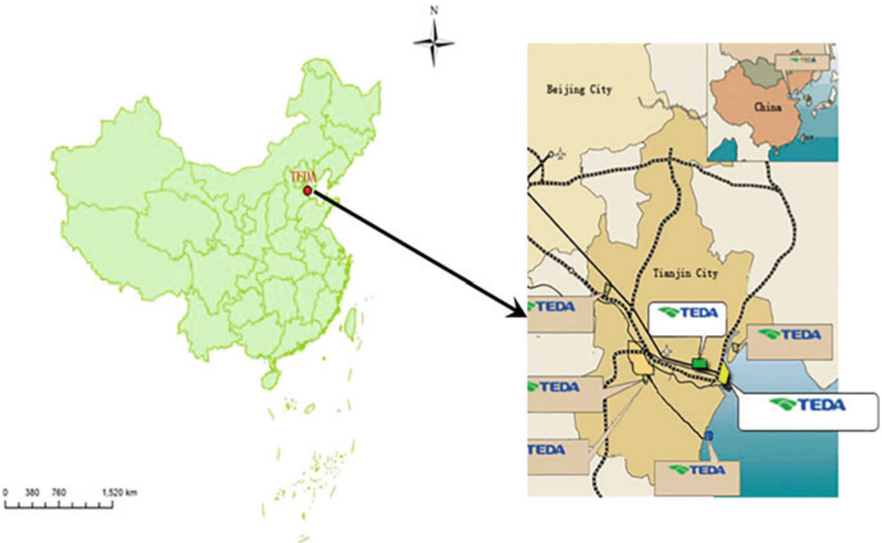

Fig. 3.1 The location of TEDA (Liu et al. 2016a)

In order to advance CED in TEDA, TEDA applied two specific strategies. One is improving enterprises' own CED capacity. For instance, TEDA encouraged the ISO14001 environmental management system. TEDA also developed an industrial symbiosis network. Based on enterprises such as Samsung, Toyota, and Novozymes as anchor companies, TEDA established the industrial symbiosis (IS) network to circulate and reutilize byproducts and waste resources. To date, approximately 250 companies have joined the network to circulate their byproducts and waste, realizing more than 40 cases of byproduct and waste exchange (See Fig. 3.2). Through the implementation of this strategy, waste to landfills has been reduced by 250,000 tons, and CO_2 mitigation amounting to 42,000 tons. Apart from establishing IS network, TEDA also encouraged new technologies such as ground source heat pumps, green water conservation, and desulfurization transformation for boilers to achieve the CED objective. In terms of water conservation, TEDA developed the first national artificial wetland and lake to regenerate water for various uses, including landscaping. TEDA has established a comprehensive system for water and wastewater utilization. For solid waste management, TEDA has a center for processing 1000 tons per day electroplating effluent and established two companies with the capacity of 90 tons per day and 80 tons per day for dealing with electronic waste and lead resource reutilization respectively. In addition, TEDA generates electricity using garbage which cannot be recycled or reused, with a capacity 400,000 tons of garbage (Liu et al. 2018c).

In order to advance CED in an industrial park, relying only on government would not achieve the goals. In this regard, TEDA has developed a number of mechanisms namely "identifying key enterprise actors, public participation, media dissemination,

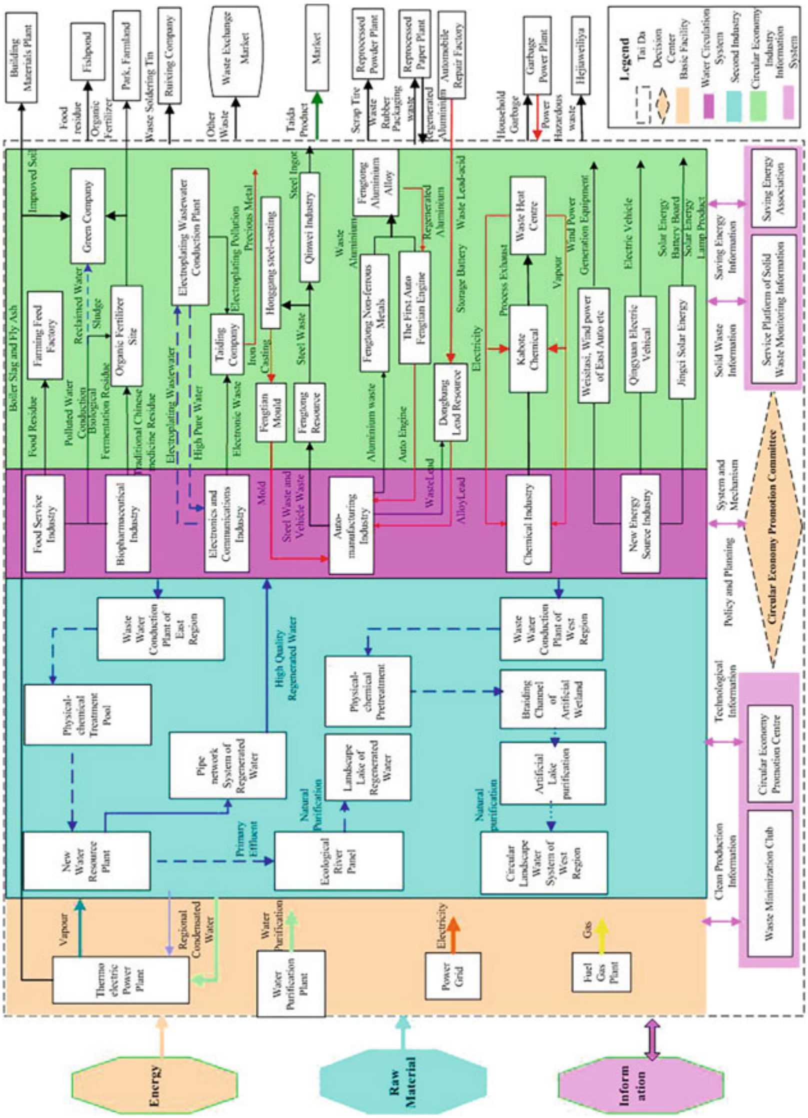

Fig. 3.2 Industrial symbiosis network of TEDA (Liu et al. 2018c)

and international cooperation" (Liu et al. 2018c). TEDA has formed a social system for resource conservation and environmental protection. For instance, the government of TEDA demonstrates its commitment to conservation of resources firstly by requiring electronic waste in the administration office to be collected for recycling and reuse. In the case of enterprises, TEDA encourages the local enterprises to disclose their environmental information and increase their environmental awareness. In addition, TEDA expects enterprises to designate champions for their environmental initiatives every year. By doing so, TEDA aims to increase the enterprise's awareness for social responsibility. Interacting with the public is another strategy for TEDA to develop CED by building green schools, organizing activities for families and supporting environmental non-governmental organizations.

There are a number of other industrial parks like TEDA in China which have initiated programs and practices related to CED. For instance, Suzhou Industrial Park has adopted the ISO14000 environmental management system and was approved as one of the first patch EIP demonstration projects by MEE. In this regard, Suzhou Industrial Park attracted globally important enterprises to invest in Suzhou Industrial Park and commence their business in Suzhou such as Nippon refinery from Japan, Mandarin Oriental from Shanghai, Jialong Technology from Fujian province, etc., which are dedicated to addressing industrial waste generated in Suzhou Industrial Park in terms of recycling, conduction, and reutilization (Lin et al. 2020). In recent years, Shenyang economic technological development area (SETDA) took the path of CED in order to promote resource utilization efficiency and reduce environmental pollution. In order to achieve this goal, SETDA has been dedicated on the field of saving energy consumption and reducing emissions. In 2013, SETDA was approved as an eco-industrial pilot project by MEE of China (Liu et al. 2019a). During the 5-year plan from 2006 to 2011, the Dalian Economic and Technological Development Zone (DETDZ) made major advancements in the field of energy saving and emission mitigation through the implementation of CED strategies. For instance, during that time, energy consumption per GDP decreased by 20.8% and water consumption per GDP decreased by 24.2%. The reutilization ratio of regenerated water to fresh water increased from 16 to 40%. The solid waste collection increased from 81.8 to 98%. The comprehensive use of fly ash increased from 68 to 85%, etc. (Liu et al. 2016b). In sum, progress is being made in many multi-sectoral EIPs across China. Given the scale and scope of these parks, this process of transformation into CED will take many years. Setting standards has given managers of these parks some guidance on how to proceed.

3.3.2.2 Sectoral Case Studies-Chinese Plastic Recycling Industry

While China has arguably put more emphasis on multi-sectoral parks, they are not ignoring sectoral industries. It can be argued that China's strong economic growth was achieved at the expense of natural resources and environment as industries grew. Chinese governments have realized this problem. Therefore, in recent years, China has been endeavoring to enhance resource utilization efficiency. CED is considered as one way to achieve this goal. Chinese leaders proposed the concepts such as "ecological civilization" that was one of the five goals in the country's overall development plan at the 18th National Congress of the Communist Party of China in 2012 sending a positive signal to encourage more environmentally appropriate development in China. The key tenets of ecological civilization are to respect, protect, and adapt to nature, which is a commitment to resource conservation, environmental restoration and protection, circular and low-carbon pathways, and sustainable development. In particular, in recent years, the issue of global extensive greenhouse gas (GHG) emissions has been a serious concern around the worldwide community. Climate change poses a fundamental threat to habitat, species, and people's livelihoods. There is a broad consensus that anthropogenic GHG emissions have contributed significantly to global climate change (IPCC 2007). With rapid economic development and urbanization, China is now the world's top GHG emitter. In 2020, China released an estimated 10 billion $CO_{2e.}$

In order to address the issue of GHG emissions, in 2020, Chinese president Xi Jinping made the commitment to the world that the objective of GHG emissions reductions for China would reach its peak in carbon dioxide emissions in 2030 and carbon neutrality would be achieved in 2060. In the past few years, in order to reduce GHG emissions, the Chinese government has implemented various energy programs to promote energy efficiency. For instance, the NDRC announced "national energy intensity targets" in accordance with the national "Five-Year Social and Economic Development Plan" (Geng 2011) aiming at improving energy efficiency across sectors. However, in order to achieve the goal of the peak carbon dioxide emissions in 2030 and carbon neutrality in 2060, apart from transforming current energy systems to a low-carbon energy system (McCollum et al. 2018), other strategies such as CED should be implemented simultaneously. There is evidence that CED will be an effective strategy to reduce GHG emissions.

One sector where this is occurring is the plastics industry. For example, plastic production relies largely on fossil fuels and consumption generates a large percentage of global waste by mass, with increasing public concerns of the environmental impacts of post-consumer plastics waste. Integrating the concepts of CE in this industry was deemed an effective strategy since its inception about 10 years ago. As a result, the Chinese plastic recycling industry (CPRI) was established and has developed rapidly under the auspices of national supportive policies. For instance, in order to encourage the expansion of CPRI, the specific CPRI zones were established in some national-level circular economy industrial parks.

From a published study (Liu et al. 2018b), it can be seen that the CPRI could contribute to the reductions of greenhouse gas emissions. It has demonstrated that over the past decade, the level of GHG emissions reduction within the CPRI has increased from 7.67 MT in 2007 to 14.57 MT in 2016 (see Fig. 3.3), which represents approximately 0.1% of the national total GHG emissions. The scale factor $\triangle S$ (referring to the ratio between the total mass of plastic waste generation and size of the human labor pool within the CPRI) and structure factor $\triangle R$ (referring to the current development size of recycling plastic waste) had significant influence on this trend (see Fig. 3.4). Vast amount of plastic waste resources and increases in the amounts of recycling plastic waste were the primary driving forces for GHG emissions reduction in the CPRI during this time. Results show that although the

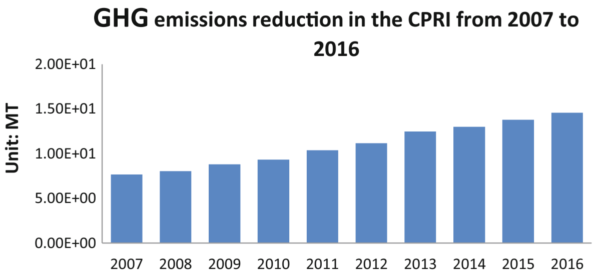

Fig. 3.3 GHG emissions reduction in the CPRI from 2007 to 2016 (Liu et al. 2018b)

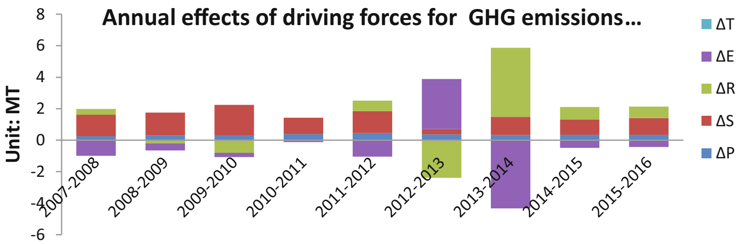

Fig. 3.4 Annual effects of driving forces for GHG emissions change in the CPRI from 2007 to 2016 (Liu et al. 2018b)

CPRI sector developed quickly in regard to processing techniques, compared to the effects of the scale and structure of Chinese plastic waste generation, the impacts of economic efficiency △E (referring to the economic efficiency in the CPRI) and technological advancement △T (referring to the GHG emissions reduction generated by unit GDP in the CPRI) were much lower (Liu et al. 2018b). Building on the trends identified in this study, as well as incorporating the potential implications of new relevant national strategies, a scenario analysis for the next 15 years has been completed.

The development of CPRI is directly linked to the global plastic waste trade (GPWT) between China and trading countries for waste reutilization. Since 1993, global annual imports and exports of plastic waste have rapidly increased, having grown 723% and 817% in 2016 respectively (Brooks et al. 2018). Developed countries have overwhelmingly been the primary exporters of plastic waste to developing countries since 1988, contributing 87% of all exports, valued at $71 billion USD. GPWT between China and trading countries increased rapidly during the last 25 years, with the highest value in weight of 8.88 MT in 2012, accounting to over 50% in GPWT, and attributed to rapid development of CPRI. The main traders in GPWT with China were the European Union (EU), United States (US), and Japan respectively. These three countries accounted for approximately 70% GPWT by weight in total China’s GPWT (Liu et al. 2021).

The reductions of GHG emissions from 1992 to 2017, in GPWT between China and trading countries, rose rapidly due to the GPWT’s development. In this regard, the net value of GHG reductions reached a peak of 8.27 MT in 2012 which is approximately one-sixth of GHG emissions of Sweden throughout the entire year (List of countries by GHG emissions, 2014), and nearly 84 times higher than it was in 1992. Liu et al. (2021) also demonstrate variation in some years, such as between 2008 and 2009 and between 1995 and 1997, which is likely the result of the global trade situation since during that period when there was a global economic crisis. Under such circumstances, the GPWT was affected by the global economic situation.

The Chinese government announced an import ban of 24 categories of recyclables and solid waste, including plastic, textiles, and mixed paper in 2017. The ban announced by the State Council of China embraces the concept of ecological civilization to achieve future economic growth. The ban also demonstrates that China aims to develop its own domestic recycling system for solid waste. China's goal for domestic solid waste recycling will increase by more than 42% from 246 million tons in 2015 to 350 million tons in 2020. This projected increase in domestic recycling and increased environmental awareness within China has resulted in the ban on importation of recycled plastic waste imposed by China (Liu et al. 2018d). This situation could spread to other sectors. Adopting CE strategies within the CPRI could be a win-win strategy—reducing plastic waste while mitigating GHG emissions. Diverting plastic waste in order to offset the use of virgin materials in plastic production positively contributes to GHG emissions reduction. However, due to the complexity of the supply chains associated with plastic waste, the nature and scope of the relationship between plastic waste and GHG emissions at a national scale requires further study as it contributes to the expansion of the CE (Chen 2016; Ohnishi et al. 2016).

3.3.2.3 Methodology Development

One of the important functions undertaken by researchers is methodology development. Researchers in academia have been developing methodologies for testing and assessing the success of CED initiatives for many years in various countries including China. These methodologies include Material Flow Analysis (MFA), ecological capacity, eco-efficiency, environmental impact assessment (EIA), and multi-criteria evaluation (Adams and Ghaly 2007; Zhang 2010; Geng et al. 2010, 2013; Wesley 2011; Zhang et al. 2011; Point et al. 2012; Rugani and Benetto 2012; Liu et al. 2015). In terms of quantitative methods, there is life cycle assessment (LCA), material flow analysis (MFA), emergy analysis, and the system of environmental economic accounting (SEEA). Taking emergy analysis for example, it has been the focus of a number of researchers. As a system method (Odum 1996), emergy analysis can be used to evaluate the interplay of industry and environment. It is an integrated evaluation method for ecological-economic systems, which has been successfully applied to systems of different scales (Brown and Ulgiati 2004). Emergy analysis specifically solar emergy, is "the available energy of one kind (usually solar emergy joules) used up directly and indirectly to generate a service or product". Therefore, solar emergy (seJ) is the common units for emergy analysis. In recent years, emergy analysis has been applied in industrial systems such as found in EIPs and industrial networks (Wang et al. 2005, 2006; Geng et al. 2014, Liu et al.

2014) where a supply-side, emergy-based indicator approach was reported to help track the entire "production cost". In order to be efficient at different levels of industrial symbiosis, new emergy indicators would be proposed including both intensity indicators and performance indicators. As Geng et al. (2013) indicated, intensity indicators target convergence of resources per unit of product, of labor expended, of Gross Domestic Product (GDP) generated, of land developed, etc. Performance indicators would include metrics such as emergy yield ratio (emergy return on emergy investment), emergy loading ratio (a measure of carrying capacity), emergy density (emergy use per unit of time and area), emergy sustainability indicator (an aggregated measure of yield and environmental pressure), emergy investment ratio (emergy investment from outside for a local resource exploitation), and fraction of emergy that is renewable, among others, all of which support multiple performance aspects in resource use.

However, with regard to practical application, methodologies have evolved from a single-method approach to hybrid methodologies as there is no one single evaluation method that could provide clear guidance on how to optimize the nature of complex industrial synergies. Hybrid methodologies have been proposed to combine the advantages of various methods so more holistic CED strategies could be implemented to optimize waste and emission management, reuse and recycle strategies. For instance, Ren et al. (2010) employed emergy-based strategic environmental assessment to evaluate the sustainability of five policy scenarios within the Chinese paper industry. Duan et al. (2011) integrated emergy analysis and LCA to investigate the Green Lake Urban Wetland Park (GLUWP) of Beijing, in terms of its environmental and capital inputs, ecosystem services and organic matter yields, environmental support, and sustainability. Liu et al. (2016a) further developed an emergy-index decomposition analysis (IDA) hybrid model to assess the impact of integrating CED into DETDZ; the model integrated emergy synthesis, impact, population, affluence, technology (IPAT) formula and IDA methods (Liu et al. 2017). In sum, research methodology has undergone rapid development in the past few years in terms of theoretical investigation and practical approaches. Researchers in Chinese universities have been especially busy in this context. Various methodologies and models have been developed and put into use in practice.

3.4 Discussion

In China, the central government plays a key role in development and implementation of CED and the SDGs. Eventually, this requires collaboration with the local government, state-owned enterprises, and eventually private enterprises. It can be seen that CED in China is not only promoted by the central government, but local governments are also enthusiastic as can be seen by TEDA in the city of Tianjin. This is demonstrated by their funding for CE projects as well as the coordination of initiatives associated with CE projects. However, as mentioned above, the practices and implementations of CED are diverse in China and increasingly there are also projects that are organized totally based on the market mechanism, which means there is little or no government involvement.

Although significant progress has been achieved in CED practice in China in terms of law, policy, project implementation, as well as methodology development, there are still a number of challenges ahead. First, from a methodology perspective, there is a limited body of knowledge surrounding the evaluation of efficiency improvements within multi-sectoral and sectoral industrial systems that integrate CED at various levels and scales. Ultimately, it is believed that the application of CED results in beneficial improvements in resource efficiency within the participating industrial network. However, quantitatively evaluating these benefits, or perhaps more importantly, having a quantitative framework for guiding the optimal development of such networks remains elusive. For instance, although there exist approaches that can evaluate various performance metrics associated with CED, none are capable of taking a holistic, multi-criteria approach that incorporates site-specific characteristics, challenges, and opportunities associated with the particular locale of the network.

In addition, there are different benefits for societies, and different degrees of complexity. Different kinds of waste utilization result in different effects. Determining the best use of the resource should include multiple factors that integrate environmental and economic considerations at various scales. It is suggested that any evaluation system and corresponding indicators should be developed utilizing multiple methods to enable the evaluation of efficiencies at different levels of CED. There are various reasons to justify the development of a hybrid model for this purpose. The comprehensive development of a CED configuration must consider regionally specific constraints such as space, finance, and disruption level. An understanding of local assets, material flows, resource needs and excesses, infrastructure, etc. will guide design decisions such as what facilities should be included in network, and what synergies are most effective (Liu et al. 2017).

Second, due to China's large size and regional disparities, resource endowment and economic development perspectives in different provinces are quite different. As a result, the national policy may need to be modified to meet local circumstances. For instance, in the more developed eastern coastal regions, economic development levels have been improved considerably such that officials and citizens have an increased desire to adopt and implement pathways to enhanced sustainability. This could suggest that such regions are more open to applying CED strategies in response to the resource and environmental issues. Some of the less developed western regions are still struggling to meet basic needs, and therefore there is more concern specifically with their economic development rather responding to resource and environmental issues. In such situations appropriate policy is important to guide effective CED development, providing the necessary incentives for companies to move forward. While modern policy-making prescribes the use of the best available information, evidence-based policy-making is relatively new; and the challenge lay in part with the large quantity of information that could inform decisions (Liu et al. 2017). In this regard, decision-makers and researchers must examine the information arising from various research domains that is regionally appropriate giving particular attention to the interface between research and policy decisions. If the specific aim is to implement CED as a strategy, policy makers require information to aid in the effective development, implementation, and management of such industrial networks, including the creation of scenarios for optimal reduction, reuse, and recycling of various material flows. All enterprises, from small businesses to large multinational corporations are connected with each other, organized as larger economic systems or webs. However, these companies may not appreciate the exact scope of the connection between each other due to information barriers. Therefore, an information system adopting a systems approach is necessary for decision-makers to establish effective systems for sharing information in order to guide the stakeholders to respond to CED targets.

Third, incomplete mechanisms to implement CE on the ground still exist. Although CED has made progress across the globe and in China by establishing an extensive policy framework, one of the key challenges is effective financing (European Commission. 2019). CED in China is still at the early stage from the financing perspective. Even though many CE projects are sponsored by governments, the general banking and financing system is constructed based on traditional business development schemes, and thus CE projects do not yet have equal access to financing support as the traditional businesses. In addition, the second-hand market is not comprehensively supported in terms of its regulation, with the result that it is underdeveloped. In order to further promote CED in China, the governments need a more comprehensive approach including in economic, social, and behavioral dimensions.

3.5 Future Research Work

In the past decade, research on circular economies has intensified. More nations have recognized the potential value of CED leading to sustainability (Liu et al. 2019b). However, the emphasis of the CE efforts in China to date has been on EIPs, circular economy parks, industrial clusters, and industrial symbiosis. Therefore, there is a need to expand the scope of policies and initiatives involved in developing a comprehensive CE within China. A wide range of research studies would support this initiative. Possible research directions in the future with regard to CED are described briefly as follows:

One research direction is associated with materials and energy circularity. The key issue around this relates to the secondary materials generated and energy input when some materials are recycled. Therefore, the question is whether the secondary materials and energy can at least offset the materials and energy consumed by raw materials processing should be further investigated.

Research associates with social science. Arguably CED requires a multidisciplinary and interdisciplinary perspective. For instance, a comprehensive CE has serious policy implications on the appropriate role of government. There are also societal implications requiring changes in behavior. These must be understood.

Another research area is material science. Currently, there are many products manufactured in China that cannot be effectively reused or recycled such as most plastic products. Under such circumstances, eco-designing a product from the material perspective in order to be reutilized is key for the product's circularity. In this regard, the research on product design and material selection are key to materials cycling.

Research on supply chains is needed. A complete recycling market with supply chain is essential. Establishing a stable supply chain suggests that a traditional one would be replaced. In this regard, shifting from the traditional supply chain to the circular supply chain involving reverse logistics will require some novel initiatives.

Research on effective financial policies and instruments is necessary. Currently, the financing system is established based on the traditional economic model. There are many hurdles from the financial perspective in terms of loans, borrowing, and valuation. Therefore, establishing a green financing system in China will require further investigation.

With the development of intelligent and digital techniques, there are opportunities to advance CE. Blockchain is one such technology. Thus far, intelligent and digital techniques have dramatically reshaped the traditional market such as the emergence of electronic business and internet tools. In the future, the potential use of these new technologies for fostering circularity should be researched. There is a link between CE and climate change mitigation and adaptation. As China moves toward a goal of addressing both issues simultaneously, the implications for government, industry, and society need to be understood.

3.6 Conclusion

In the past 20 years, China has made substantial progress in the development of a CE. The national government in China has taken a leading role in advancing CED in terms of policy making and guidance. In addition, Chinese scholars are paying more attention to CED, and research outcomes in this regard have demonstrated a rapidly increasing trend. Under such backdrop, the awareness of waste reutilization and recycling among Chinese industries and society has gained some ground. With the development of CED in China, it can be seen that the concept is being recognized under the leadership of governments, bridged by academia, which will impact production behaviors among enterprises and consumption behaviors eventually among Chinese civilians and enterprises. The transition from the traditional ones to a more circular type of economic and industrial activity will take time but the right policies seem to be in place.

CED in China has its own unique background and pathways. China is a very large country with a massive population. The resources are limited on a per capita basis. In the early stage of opening up and reform, the enterprises were mostly low-efficiency enterprises, which consumed large quantities of resources and China paid an environmental price to maintain its economic growth. After 20 years of opening up and supplying the world with products, the national government has realized the importance of taking an ecological civilization pathway to drive the economy in the future. CED has been selected as the national strategy to drive the domestic economic development meanwhile saving resources and reducing environmental pollution. In this chapter, CED in China is introduced in terms of its unique strategies, policies, and practices. In particular, this chapter analyzes the unique CED pathways in China, as well as the role universities have played in advancing the idea across the country.

In recent decades, traditional linear industrial development has contributed to massive waste generation, excessive resource consumption, and frequent environmental events. In this regard, CED can be considered an important part of the solution toward achieving sustainable development goals. However, from a global point of view, the concept of the CE is still at the early stage. There are still many barriers including from the perspectives of system, information, financing, and even ideology. In the future development, how to respond to these challenges is important to achieve CED. Apart from the systematic reform to the traditional economic and finance mechanisms, the integration of modern intelligent and digital techniques seems to be especially promising. The integration may help to break through the physical barriers and solve issues such as information asymmetry.

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4 Circular Economy Policies and Innovations in Africa: Pillars for Achieving Sustainable Development

Michael K. Koech, Kaburu J. Munene, Mary Kanyua Kinoti, and Desmond Khisa Situma

Abstract

Africa is the fastest urbanising continent leading to increased consumption of resources and generation of waste. Studies indicate that by 2060, the continent's population will be approximately 2.8 billion. The increase in Africa's population will further increase consumption and production patterns. Therefore, the continent needs to shift from a linear economy to a circular economy that is a more economical and ecologically form of sustainable development. In Africa, a sustainable circular economy will include better-informed harnessing of resources and sound waste management to meet the population's needs and achieve several sustainable development goals (SDGs). This study relied on a desktop research design to gather well-grounded data on African circular economy policies and innovations. Data revealed that several African countries have begun strengthening their governance to initiate circular economy aspects in policies and innovations. For example, African governments empower youth and women groups, particularly from the slums and university scholars, to develop innovations to boost circular economy practices. Similarly, skilled experts are teaming up to form regional organisations like the African Circular Economy Network (ACEN) to promote waste management creativity and

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economic productivity. This paper ascertains that African governments have more opportunities to shift from a linear economy to a circular economy. The continent boasts of many skilled scholars, policymakers, and indigenous communities that can engage in a participatory approach to design effective policies and innovations that integrate circular economy practices that uphold the principles of sustainable development.

Keywords

Circular economy · Cleaner production · Industrial ecology · Sustainable development · Sustainability

4.1 Introduction

Contemporary development models are shifting towards the inclusion of sustainable development goal recommendations in policy and practice. However, the extent to which such propositions are implemented varies in countries and across sectors. To catapult sustainable development, governments must create a socio-economic atmosphere that allows access to technology and spearhead a culture of innovation. It is such initiatives that facilitate sustainable transitions towards a circular economy. Linear economy models focus on waste production, consumption, and generation, and not much effort is put into reducing waste.

On the other hand, a circular economy implies an economic system of production and consumption that targets to create further value from products through sharing, reusing, repairing, refurbishing, and recycling (Geissdoerfer et al. 2017). Such a system aims to ensure a product's extended life cycle and keep waste generation as minimum as possible. The circular economy system also constitutes many initiatives by different sectors to ensure that cumulatively more value is derived from products and efficiency is met across the cycle, from design, through production to consumption, than waste management. An interesting characteristic of a circular economy is that it goes beyond the economy and creates an equilibrium with other domains of development, such as the biophysical environment and society.

Within this framework, the principles of people, planet, and profit are derived to drive the private sector activities and enterprise. One of the critical factors to the success and adoption of a circular economy is embracing technology and innovation, but this should be carefully done to ensure optimal value creation.

4.1.1 Methodology

This study adopted a desk view research design. Desk view research design entails using existing scholarly data to find more information about the research phenomenon in question. This study incorporated peer-reviewed and credible secondary data to acquire more information about African circular economy innovations and

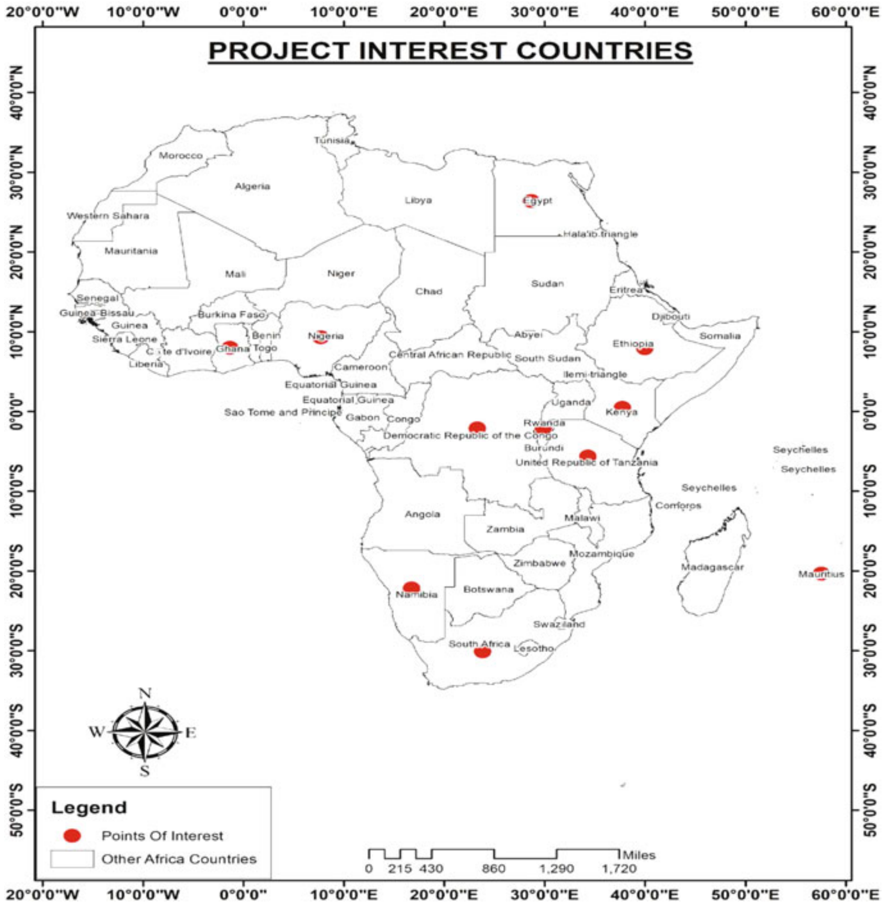

Fig. 4.1 Map of African countries. (Source: Authors)

policies. The secondary data sources were journals, books, periodicals, newspapers, government statistics reports, and credible internet sources. This research study was limited to funding. Thus, utilising a desk view research design was instrumental in cutting the cost as it promotes research using secondary data instead of fieldwork to collect raw information. The study utilised quantitative and qualitative data to provide more information about African circular economy policies and innovations. Figure 4.1 indicates the countries that this study examines. The countries include Kenya, Rwanda, Tanzania, Ethiopia, Mauritius, Egypt, Ghana, Nigeria, the Democratic of Republic of Congo (DRC), Namibia and South Africa.

4.2 Sustainable Development Goals and Circular Economy

In the twenty-first century, the globe began to realise that economic growth will lead to massive environmental risks. Rodríguez-Antón et al. (2022) note that their several earth summits were organised since 1972 with the assistance of the United Nations (UN) to provide space for world leaders to identify pathways for sustainable development. The global concern to stimulate sustainable economic growth led to the production of the Brundtland Report in 1987. The report brought to the limelight the term ‘sustainable development’ for the first time (Rodríguez-Antón et al. 2022). The Brundtland Report of 1987 underpinned global efforts to rethink economic development practices and policies that champion the reduction of ecological destruction.

In September 2001, the UN mandated the ‘Declaration of the Millennium’ to protect humanity and promote international relations (Fehling et al. 2013; Rodríguez-Antón et al. 2022). Fehling et al. (2013) pinpoint that the ‘Declaration of the Millennium’ brought about the Millennium Development Goals (MDGs). The MDGs were a list of common targets for the globe to attain by 2015 voluntarily (Lomazzi et al. 2014). Rodríguez-Antón et al. (2022) highlight that in 2015 the UN approved the ‘Agenda for Sustainable Development’ that paved the way for the SDGs generation. The SDGs have targeted measures to guide humankind to shit to environmentally-friendly practices. The implementation of the SDGs calls for a participatory approach and collective action that allows various stakeholders to share knowledge resources and actively cooperate in implementing sustainable practices.

One of the measures to assist the global community shift to sustainable practices is responsible consumption and production, specifically circular economy. Sutherland and Kouloumpi (2022) note that aligning circular economy to sustainable development is a transformational shift towards creating liveable spaces. Research indicates that a circular economy is linked to several SDGs such as Goal 6-*clean water and sanitation*, Goal 7-*affordable and clean energy*, Goal 8-*decent work and economic growth*, Goal 12-*responsible production and consumption,* and Goal 15-*life on land* (Schroeder et al. 2019). In addition, Schroeder et al. (2019) point out that a circular economy has the potential to support the achievement of more social SDGs such as SDG 1-*no poverty*, SDG 2-*zero hunger*, SDG 3-*good health and wellbeing*, SDG 5-*gender equality*, and SDG 10-*reduced inequalities*.

An in-depth literature analysis reveals that the two variables, circular economy and SDGs, have a significant positive relationship (Valverde and Avilés-Palacios 2021). The two concepts are intertwined as a circular economy positively impacts humanity to transition to healthy living spaces that create an equilibrium between economic, social, and environmental pillars of development. Individuals, companies, and countries are incorporating circular economy practices and SDG recommendations into their practices and operations to have a competitive edge in ecological protection, innovations, and employment creation to boost living standards. Data indicate that Africa lags behind in the industrialisation sector and economic growth than Asia and the Pacific region (Andersen et al. 2021). However, many African countries have begun implementing and targeting rapid industrialisation policies and practices to spur economic growth (Opoku and Yan 2019).

The massive industrialisation across the continent provides an opportunity to integrate circular economy practices and SDGs' recommendations into policies, strategies, action plans, and operations. The African circular economy is recognised as a vibrant and innovative system providing circular solutions mainly inspired by waste management conditions. Policymakers in the continent discern that intertwining circular economy and SDGs into national development will play a crucial role in attaining broader sustainability goals and objectives (Anderson 2021; Ellen MacArthur Foundation 2021). However, since the continent is still in rapid economic development, there is still a great opportunity for adopting more effective and sustainable practices to create a resilient social and environmental living space.

4.3 Opportunities and Importance of Circular Economy Policies and Innovations

A Circular Economy is an economic model whose main objective is to produce goods and services in a sustainable way by limiting the use of waste and raw materials as well as the production of waste. A circular economy aims to use waste and recycle them into raw material for product remaking and to be used for other purposes. A circular economy applies the principles of a green economy, industrial ecology, and eco-design (Klein et al. 2013).

CE involves reusing/redesigning waste materials to make them longer lasting and reusable. This approach also helps in keeping away waste from landfills and also trying to recover valuable resources. According to Klein et al. (2013), CE is an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It is a system that aims to accomplish sustainable development that eventually creates environmental quality, economic prosperity, and social equity to the benefit of current and future generations (Klein et al. 2013).

The CE is a relatively new concept in Africa and will benefit the countries on the continent. This has a promising opportunity for the economic perspective that includes creating job opportunities for the youth. CE will also create environmental opportunities to be practised that promote environmental sustainability (Stubbs 2019). A circular economy is crucial for African countries because of its economic and environmental impacts on the continent. Some African countries have already implemented strategies that are in line with CE by developing a green economy that will feed into it. Examples of these countries are Kenya and South Africa, whose case studies will be discussed below.

4.3.1 Importance of Circular Economy

CE is essential in breaking the linear economy already affecting the planetary boundaries by exceeding it (IRP 2017). CE, however, is based on achieving both environmental and economic benefits. The impact it will have in Africa is predominantly aimed at reducing poverty, environmental pollution, and inequality, which are some of the sustainable development goals. Recent research demonstrates a positive relationship between a circular economy (CE) and achieving some sustainable development goals (Valverde and Avilés-Palacios 2021). Schroder et al. (2019a, b) established a strong relationship between CE and SDGs 6, 7, 8, 12, and 15 and further argued that indirect relationships exist among the other SDGs. For example, the achievement of SDG 6 on the improvement of clean water and sanitation establishes good health and wellbeing (SDG 3). On further examination, we find that achievement of SDG 8 positively impacts SDG 1, 2, 3, 4, and 5.

Despite the progress towards achieving economy-related targets by 2030, the sustainability of cities and communities lags behind (Sutherland and Kouloumpi 2022). The duo advances that "…the circular economy comes in: by circulating resources multiple times, the circular economy tackles issues of scarcity and allows all to access what they need—without overburdening the earth…".

A circular economy has a higher chance of reducing costs and preventing market price fluctuations (Ellen MacArthur Foundation 2013). Through using the five Rs (reduce, refuse, re-use, recycle, repurpose), the same products will be reused to prevent waste, thereby reducing the expenditure of purchase and disposal. This will encourage the stability of products manufactured in African countries. Products can be put in a production cycle to recycling to avoid waste from the industries being released into the environment. These innovations will also create an enabling opportunity for the creation of employment in the continent.

A circular economy will encourage the use of renewable energy since the materials meant for disposal can be used as an alternative source of energy (Ellen MacArthur Foundation 2013). This will also encourage the creation and innovation of new products that can be used as energy sources instead of the natural methods we use, such as wind. Through having several energy sources, fossil fuel use can be reduced, thus cutting down on the amount of pollution in the continent. Having alternative sources of energy will also heavily help in cutting down on overdependence on using charcoal, firewood, and deforestation in the long run.

A circular economy can potentially address poverty reduction in the continent by providing a route to supporting the human development of African countries through the CE 2.0 framework. This will be done by creating employment and designing profitable business models for the continent (Schröder et al. 2020). The innovations that would be encouraged will be a window of opportunities for individuals to develop their self-sufficient way of earning a living and improving their livelihood. Job creation in the continent is essential to reduce the number of unemployed people and reduce the high poverty rates in the continent at large. This will help raise the economic status of the countries.

A circular economy can potentially improve people's livelihoods in developing countries. This can be done by creating more sources of employment opportunities and creating an enabling environment through encouraging innovations (Fernandes 2016). Having more employed people will be beneficial in raising the economic status of the country, reducing poverty levels, reducing crime rates, and also ensuring general economic growth for the continent.

A circular economy will provide a chance for other economic issues such as waste management, disposal of electronic waste, energy needs (including the use of renewable energy), poverty reduction, and job creation (Gower 2016). These issues have been dealt with in a linear manner, thus causing their management to go out of hand. For example, waste management in most African countries usually depends on getting rid of the waste in sanitary landfills or burning. This has proven to have negative impacts such as pollution, loss of aesthetic value, and making land to be unable to be used. CE will provide an opportunity to reduce the amount of waste being thrown away by prolonging the use through recycling, thereby helping solve one of the most important environmental issues, pollution.

4.4 Circular Economy Innovation Policies in Africa

4.4.1 Overview of Circular Economy Policies and Innovations in the Continent

According to Braun and Toth (2020), the circular economy in Africa has been implemented as a restorative process of transforming the traditional approaches of economic production and general consumption into new systems that seek to prioritise environmental conservation goals. As a result, the continent is focusing on adopting circular economy innovations that have proven to create value in different aspects of business operations, with the main considerations of the start-ups and SMEs, attracting investors to support the sustainable development within the region. In the process, leveraging FinTech and sustainable financial support has been observed as a key element towards the continent's circular economy innovation growth (Ghosh 2020). Similar views by Bag et al. (2020) indicated that most African countries seek to intensify their industrialisation while pursuing green growth to improve competitive growth, hence, considering a circular structural change. In the process, the continent perceives the resource supply as a more important incentive than cutting costs. Therefore, the African continent is currently transforming its operational strategies to support a circular economy.

Ramakrishna et al. (2020) noted that implementing a circular economy in Africa faces financial challenges, which creates limitations towards attaining sustainability goals. As a result, there is poor resource planning and utilisation, leading to reduced launching of innovations in the country. Some African countries have failed to attain the circular economy goals because of the capacity variations that affect the process of implementing circular economy practices. Lack of sufficient capacity has also forced some African nations to adopt sub-standard solutions that have long-term costs. Ghisellini and Ulgiati (2020) noted that the capacity limitations had affected the reliability of the decisions made by the leadership teams because their decision-making process is influenced by the prevailing resource capacity characteristics. However, Schröder et al. (2020) recommended that proper planning provides a key mechanism towards the formulation of solutions that can receive external support, hence, helping the continent attain sustainability.

Resistance from the top country leadership creates a barrier towards the execution of sustainable goals in the market (Ramakrishna et al. 2020). Some African leaders lack sufficient understanding about the need and impacts of adopting circular economy practices, hence, leading to reduced support of the efforts in place. Some national leaders expected to support the circular economy initiatives have underlying personal interests that affect the general effectiveness of policy formulation and the implementation exercise. However, Ghosh (2020) argued that lack of support has mostly emanated from the overreliance of the African economy on the extractive industry, which is the key point of transformation before the achieving of the circular economy within the area. As a result, the industry provides a source of income to most citizens and the country in general through employing most skills within the nation (Schröder et al. 2020). In the process, efforts to adopt new strategies in support of the circular economy implementations that counter the lucrativeness of the extractive industries often lead to resistance. Therefore, the overreliance on this sector leads to increased resistance from the citizens, political leadership, human rights groups, and other beneficiaries of the companies, which creates a barrier towards the execution of the desirable circular economy factors within African countries.

Tudor and Dutra (2020) stated that the adoption of circular economic innovations has aided to open up better development avenues in host African states, confining to sustainable characteristics of resilience and resourcefulness, thus, leading Africa to a prosperous, equitable, and flourishing circular economic continent. The solutions provided with the circular economy help to improve efficiency, create time-saving models, and increase the general productivity of industries while at the same time improving resource sustainability. Conversely, Imoniana et al. (2021) argued that the African continent stands a better chance to utilise this innovation due to its low economic footprint. The diversity of natural resource capital and potential infrastructural adaptability make this region better in advancing this innovation.

Pizzi et al. (2020) revealed that since circular economic innovation was launched in the continent, there has been significant economic growth, job creation, and other sustainable environmental outcomes. The expansion of use and research on this innovation in the continent has further promoted the preservation of production capacity of critical resources, shaping existing investment policies, and improved employability in the informal economic sector (Imoniana et al. 2021). Ghisellini and Ulgiati (2020) also confirmed that circular economy provides both long-term and short-term benefits towards enhancing the continent's well-being both directly and indirectly, hence, improving the general living standards of the people and the resource sustainability for economic improvement. Therefore, a circular economic trend has transformed the existing economic patterns in the continent by creating new jobs through the sustainable use of available natural resources.

According to Skrinjaric (2020), the common circular economy policy implementation approach is the mapping of the existing initiatives into the circular system and the execution of the strategies to transform the economy. In the process, the future skills and jobs are mapped to sustainability to ensure that the continental operational activities make both direct and indirect contributions towards supporting the desired circular economy goals. Braun and Toth (2020) added that the effectiveness in the coordination of the regional and national leadership provides suitable mechanisms for supporting the adoption of the strategies of a circular economy.

Contrarily, Ghisellini and Ulgiati (2020) noted that considering the fact that the strategies adopted within the continent towards the supporting circular economy are voluntary and not compulsory, there is a high likelihood that the initiatives cannot be prioritised appropriately to support the goals. Similarly, the central played by the national leaders towards the implementation of the circular economy policies has affected the general effectiveness of the policies, leading to an increased chance of influence of political forces that increase the challenges of attaining the set goals (Braun and Toth 2020). Politics and lobbying practices are influential and affect the reliability and trueness of the sustainability decisions made by the country. Therefore, the implementation of sustainable practices through policy formulation provides a better and improved way of attaining the circular economy goals.

4.4.2 Various Continental Blueprints Like Agenda 2063, Trade Agreement, and National Circular Economy-Related Policies

Research indicates that Africa is the fastest urbanising continent in the world. The continent will have over four billion people by 2100. A significant number of the population will reside in urban areas. The continent will also experience a huge physical and landscape transformation due to the construction of major industrial plants, transportation networks, and housing to drive economic and social growth. Several governments recognise that there is an urgent need to enact circular economy policies to achieve urban sustainability. African governments are ratifying Multilateral Environmental Agreements (MEAs) such as the United Nations Paris Agreement and sustainable development goals (SDGs) to formulate national circular economy policies (Andersen et al. 2021). African governments with circular economy policies also aim to initiate smart green technologies to address severe environmental challenges like climate change and unsustainable waste management. This research discusses circular economy policies from Ethiopia, Ghana, Rwanda, Namibia, Nigeria, South Africa, and Kenya.

4.4.2.1 Agenda 2063: The Africa We Want

Africa's Agenda 2063 is a major blueprint that guides the continent to initiate sustainable economic growth and inclusivity (African Union Commission 2015). Agenda 2063 demonstrates the Pan-African unity of nations to collaborate in achieving sustainable economic development, freedom, and inclusion of all women, youth, and other vulnerable groups in development projects. The primary purpose of creating Agenda 2063 was to help nations cope with global economic activities in the post-colonialism era, which was the main advocacy of the Organization of African Unity (OAU) before transforming into the African Union (AU). Agenda 2063 was also created as a result of frustrations and a lack of sustainable economic and social initiatives in the continent compared to other developed areas like Europe, North America, and Parts of Asia. Over the years, some of the countries in the region have been relying on *foreign* aid, either food or monetary. Agenda 2063 will play a significant role in helping countries to become dependent rather than relying on foreign aid and innovations.

Therefore, Agenda 2063 aims to transform the continent into a global sustainable economic and prosperous social region within 100 years after the formation of the OAU (African Union Commission, 2015). The blueprint's vision is "to become an integrated, prosperous and peaceful Africa, driven by its own citizens and representing a dynamic force in the international arena" (African Union Commission 2015). The blueprint was adopted in 2015 during the 24th African head of states and AU leaders' assembly in Addis Ababa. However, the first advocacy for the formulation of a continental blueprint was first discussed with the head of government and AU representatives in 2013. The AU is tasked with monitoring and guiding African nations with the implementation of Agenda 2063.

Agenda 2063 will play a significant role in promoting circular economy activities and aspirations (African Union Commission 2015). One of the aspirations of the blueprint is a creation of a prosperous continent that incorporates sustainable development. The aspiration's main goals are transforming economies, adopting modern agricultural technologies, promoting blue economy, enhancing the health of the citizens, and educating and training citizens to develop scientific-technological innovations. In goal number one on the transformation of economies, Agenda 2063 guides African countries to empower industries to adopt circular economy innovations that transform waste into a raw input for the production of other products (African Union Commission 2015). African industries are encouraged to invest in research and development to create a chance for workers to develop new technologies to manage solid waste and wastewater treatment. The transformation of economy goals creates a chance for manufacturing and industrialisation plants in the continent to adopt cleaner production and industrial ecology ventures to reduce carbon emissions and industrial effluents that threaten aquatic ecosystems. Solid waste recycling and wastewater treatment also play a critical role in strengthening the economic growth of the region. Circular economic activities such as recycling waste and innovations create employment opportunities for citizens, improving their living standards.

The adoption of modern agricultural technologies goal of Agenda 2063 creates a platform for African governments to transform their crop production strategies (African Union Commission 2015). The goal requires governments to empower their citizens in developing agricultural technologies that reduce ecological damages. Agricultural activities must display a harmonious relationship with nature through activities such as reducing air pollution from farm inputs like insecticides and herbicides. Farmers must also maximise using organic waste to create manure rather than relying on inorganic fertilisers that cause harm to soil microbes and reduce soil quality. The adoption of modern technologies allows governments and farmers to engage in sustainable waste management using circular economy strategies.

The promotion of the blue economy goal promotes African governments to ratify Agenda 2063 and initiate activities such as a waste collection of plastic bottles and papers that are increasing in oceans (African Union Commission 2015). Agenda 2063 recognises the blue economy as a major economic factor that must be sustainably managed to enhance the survival of aquatic organisms to boost food security and protect coastal areas from extremes of climate change, such as coastal flooding.

Agenda 2063s goal of enhancing the health of the citizens advocates for sustainable management of ecological resources to create a conducive living environment with clean water, air, and smart green technologies. The goal encourages the implementation of renewable energy such as wind power, solar energy, and the generation of electricity from tidal waves. The goal also encourages the use of organic waste to generate biofuel to boost lightning and harmful elimination sources of energy like charcoal that emit carbon dioxide. In most urban areas in the continent, like in Mukuru slums and Kibera, there has been the establishment of biofuel generation plants to manage organic waste collected within Nairobi City. The goal of enhancing the health of the citizens is also promoted through wastewater treatment. After treating wastewater, clean water is piped back to households to help them access water for domestic use and promote hygienic conditions. Agenda 2063 goal of education and training of citizens to develop scientific-technological innovations empowers people to develop new initiatives to manage solid waste, wastewater, and promote the transformation of urban areas into ecocities.

4.4.2.2 Climate Resilient Green Economy Policy in Ethiopia

Climate Resilient Green Economy (CRGE) is the main circular economy policy in Ethiopia (Albagoury 2020). CRGE was initiated in November 2011 and aimed to transform the country's traditional linear economy into a circular economy. The ministry of environment in Ethiopia is tasked with implementing CRGE (Albagoury 2020). The primary purpose of CRGE is to reduce the effects of extreme climate change through the adoption of renewable energy. Thus, by the end of 2025, which is the end of implementing CRGE, Ethiopia will be a middle-income economy with higher resilience to climate change impacts and reduce emissions of GHGs. The CRGE draws support from three major national documentations, the Climate Resilience Strategy for Agriculture, Ethiopia's Programme of Adaptation to Climate Change (EPACC), and the Green Economy Strategy ("Ethiopia's Climate Resilient," n.d.).

The CRGE is built on four main circular economy strategies. The first pillar is the protection of forest reserves which act as carbon stocks and aesthetic value. Ethiopian government aims to reduce overexploitation of forest resources by encouraging industries to use alternative raw materials such as using plastic waste to make fencing poles. CRGE also encourages industries and citizens to a mixture of timber waste such as sawdust and cow dung to produce briquettes (Barbre 2013). The policy also plays a significant role in using organic waste from coffee which is a major cash crop in Ethiopia, to produce biofuels to reduce the cutting of trees to make charcoal or firewood.

The second pillar of CRGE is an improvement of agricultural activities such as livestock keeping and crop production ("Ethiopia's Climate Resilient," n.d.). This second pillar aims to ensure that agricultural activities in Ethiopia have lower GHG emissions. The ministry of environment in Ethiopia recognises that agricultural transformation is a major factor towards achieving a green economy ("Ethiopia's Climate Resilient," n.d.). Thus, the government will empower large-scale and small-scale farmers to make organic waste from biodegradable farm waste to reduce the use of inorganic chemicals like insecticides, herbicides, and fungicides that cause air pollution and emission of aerosols that deplete the ozone layer, causing an increase of temperature.

Expansion of renewable energy production is the third pillar of CRGE. CRGE advocates for the efficient utilisation of resources to achieve environmental, social, and economic growth. CRGE policies create a platform for Ethiopia to initiate renewable energy initiatives such as generating power from waste in Koshe dumpsite. The policy empowers waste collectors in Addis Ababa and other major urban centres in the country to collect waste and transport it to Koshe dumpsite for power generation ("Ethiopia's Climate Resilient," n.d.). Thus, instead of disposing of waste in landfills and other open dumpsites, it is widely used as raw input for the generation of renewable power.

The fourth pillar is the adoption and promotion of smart and green technologies in the transportation sector, industrial plants, and construction of housing structures ("Ethiopia's Climate Resilient," n.d.). CRGE policy ensures that Ethiopia initiates strategies to replace the use of fossil fuels in automobiles, industries, and construction. One of the major achievements due to circular economy policy in Ethiopia is the production of the first locally assembled electric car (Tekle 2020). The first electric car was due to collaboration between a renowned Ethiopian athlete, Haile Gebreselassie, and South Korean motor company Hyundai. CRGE aims to initiate several innovations to achieve sustainability in the transportation sector, industries, and housing.

4.4.2.3 Plastic Bag Law 57 in Rwanda

The Plastic Bag Law 57 of 2008 is the major circular economy-related policy (Danielsson 2017). The law prohibits the manufacture, sale, and use of plastic bags. The Rwandan government recognises environmental conservation and protection as a major priority to achieve economic and ecological sustainability. Article 22 of Rwanda's Constitution states that citizens have the right to reside in a hygienic environment. Rwanda was the first country in the East African Community (EAC) to ban the use of single-use plastic bags (Mugisha 2020). Individuals with a higher stock of plastic bags were given 3 months to sell their products. Plastic Bag Law

57 of 2008 prohibits the use of plastic straws, containers, plastic packaging materials, and plastic cutlery.

Plastic Bag Law 57 of 2008 also applies to foreign visitors prohibiting the importation of plastic bags into the country. Plastic bags are confiscated at various entry points such as airports for recycling. The Plastic Bag Law 57 of 2008 allows companies like Ecoplastic in Rwanda to collect confiscated plastic bags and plastic waste such as bottles and use them to produce construction materials. According to Tasamba (2020), in Rwanda, there are various waste recycling plants that transform plastic waste into tiles and roofing materials. Existing plastic waste in Rwanda is also transformed into fibres to make clothing.

4.4.2.4 Green Economic Coalition Dialogue (2011)-Related Circular Policy in Namibia

The Green Economic Coalition Dialogue in Namibia was initiated in 2011 to help the country transform into a circular economy (Desmond and Asamba 2019). The dialogues were supported by Deutsche Gesellschaft (GIZ). Namibia's ministry of labour and social welfare is tasked with the implementation of the policy by creating practical activities from the dialogues. The primary purpose of the Green Economic Coalition Dialogue is reducing industrial waste, enhancing recycling, and initiating renewable energy projects (Desmond and Asamba 2019). The Namibian government, through the Green Economic Coalition Dialogue, offers loans to individuals and companies to initiate renewable energy technologies (GIZ 2013). The loan is commonly referred to as the Solar Revolving Fund. The Green Economic Coalition Dialogue promotes Community Based Natural Resource Management in Namibia, allowing the production of renewable energy from biomass such as the Jatropha plant and bioethanol-containing materials (GIZ 2013). The promotion of renewable energy production by the Green Economic Coalition Dialogue plays a significant role in reducing disposable waste and maintaining the aesthetic value of the ecological surroundings. The Green Economic Coalition Dialogue also creates a chance for industrial plants to reduce harnessing of raw materials and use waste materials as a substitute for raw inputs.

4.4.2.5 National Environmental Management Act (1998) in South Africa

The National Environmental Management Act (1998) was adopted in 1998 by the South African government. The National Environmental Management Act is abbreviated as NEMA, which promotes the enforcement of section 24 of the country's constitution. The ministry of environment in South Africa is tasked with the implementation of NEMA. NEMA's primary objective is reducing waste pollution and enhancing sustainable utilisation of ecological resources (Desmond and Asamba 2019). NEMA promotes the implementation of 3R programs of waste management, recycling, reusing, and reduction. For example, NEMA promotes recycling initiatives such as using old plastic bottles to establish small urban agricultural crops to boost food security in unplanned settlements. South Africa's NEMA also empowers the creation of state agencies such as the National Environmental Advisory Forum and the Committee for Environmental Coordination under sections three and seven, respectively (FAO n.d.). The state agencies play a significant role in enforcing environmental initiatives to reduce waste. NEMA also creates a platform for the creation of public-private partnerships to engage in informed decision-making about waste reduction initiatives in industries and urban areas.

4.4.2.6 Extended Producer Responsibility Programme (2013) in Nigeria

Desmond and Asamba (2019) note that the main and most efficient circular economy policy in Nigeria is the Extended Producer Responsibility Programme of 2013. The policy is governed and enforced by the National Environmental Standards and Regulations Enforcement Agency. The primary goal of the policy is to reduce industrial effluents, waste and promote recycling (Desmond and Asamba 2019). Nigeria has been facing an increased generation of Electric and electronic waste that has harmful substances that pose health and safety risks to humans, fauna, and flora (Woggsborg and Schröder 2018). The Extended Producer Responsibility Programme in Nigeria allows producers of e-waste to showcase financial of physical responsibility in managing the waste after the consumption stage. Nigeria's Extended Producer Responsibility Programme creates a platform for e-waste producers to recycle used materials to create new materials and reduce improper disposal of hazardous substances in the environment. Producers of e-waste in Nigeria have recycling targets that must be met to promote circular economy activities. The Extended Producer Responsibility Programme allows e-waste producers in Nigeria to meet the recycling fees and other taxes to eliminate the accumulation of waste in the environment (Woggsborg and Schröder 2018). Thus, the Extended Producer Responsibility Programme promotes healthy living due to the elimination and reduction of harmful e-waste in living spaces.

4.4.2.7 Egypt Vision 2030

Egypt's Vision 2030 is also referred to as the sustainable development strategy (SDS). The policy framework was adopted in February 2016 with the aim of guiding the country to achieve sustainable development (Egypt Economic Development Conference 2015). Egypt Vision 2030 focuses on improving the environmental, social, and economic dimensions. The enactment of the policy was due to motivation from ancient Egyptian civilisation to engage in effective planning of future developments. One of the focal areas of Egypt's Vision 2030 is an investment in reliable renewable energy (Egypt Economic Development Conference 2015). The policy advocates for the use of plastic waste and organic waste to generate electricity. The ability to use waste as raw inputs in the power-generating plant will play a significant role in reducing the accumulation of waste in urban areas and vital ecological resources like the River Nile. Egypt Vision 2030 also empowers the national and regional administrations to invest in wastewater treatment and reuse (Egypt Economic Development Conference 2015). Treating wastewater and providing it back to the citizens as clean water will address water shortage issues that the country faces which hinder the achievement of an ideal hygienic condition in some unplanned settlements like in Ezbet El Haggana slums.

4.4.2.8 Maurice Ile Durable (MID) Sustainable and Circular Economy Concept in Mauritius

Mauritius launched the MID in 2008 with the purpose of guiding the country to achieve sustainable development through circular economy initiatives (Ministry of Environment and Sustainable Development 2013). The MID promotes a reduction and sustainable harnessing of natural resources to reduce extinction and overexploitation. Mauritius also utilises MID to empower citizens to create smart green technologies to tackle waste challenges (Teeluck et al. 2013). One of the major goals of MID is sound environmental management through investment in renewable energy and the elimination of fossil fuels. The concept advocates for the use of biomass waste generated from its urban areas to generate electricity and reduce carbon emissions from fossil fuels. The promotion of environmental goals leads to a significant reduction of the country's ecological footprint due to overexploitation of scarce natural resources. MID advocates for the use of waste materials to be used as raw materials in the production of products to reduce overexploitation of natural resources (Ministry of Environment and Sustainable Development 2013). Mauritius' MID aims to help the country achieve zero waste generation as it will be utilised to make products and generate electricity. The MID also promotes the polluter pays principle, forcing individuals and companies that generate waste to meet the cost of collection and cleaning the environment (Teeluck et al. 2013). Thus, a significant number of individuals and companies in Mauritius undertake recycling measures to avoid paying fines or subjecting their workers to environmental clean-ups due to improper waste disposal.

4.4.2.9 Kenya Circular Economy-Related Policies

Solid waste management has always been a challenge in Kenya. In Nairobi, dumpsites like Dandora are being used for disposal while most waste is disposed of illegally or burnt. These dumpsites are unsanitary, unplanned, and not operated on systematically. This eventually has led to air, water, and soil pollution, thereby causing health and environmental problems (Soezer 2016). Some recycling companies have started recycling plastics into building materials, furniture, and other artefacts (Koech and Munene 2020). This has created a method of reusing plastics that harm the environment and also coming up with a sustainable method of maintaining it through using it as a building material. As a result, this has helped the economy by improving the living standards of the citizens through job creation opportunities. It is also environmentally beneficial since it reduces the pollution of plastic waste (Desmond and Asamba 2019).

E-waste is among the fastest-growing waste in Kenya and the world. This is due to the importation of cheap phones from Asian countries that do not last for long (Desmond and Asamba 2019). E-waste is a serious threat due to its components which include a mix of plastics, chemicals, heavy metals, and radioactive elements, which can be harmful to human health and the environment if not properly handled. Circular economy innovations will also create an opportunity for the proper collection, disposal, and recycling of e-waste. It also provides for improved legal and administrative co-ordination of the diverse sectoral initiatives in the management of e-waste as a waste stream in order to improve the national capacity for the management of e-waste (National Environment Management Authority 2017).

Vision 2030-Kenya

Kenya's Vision 2030 is a blueprint to guide the implementation of sustainable development projects (Government of the Republic of Kenya 2007). The blueprint aims to transform the Kenyan economy into a global competitor in economic, social, and environmental innovations as well as achieving high life quality. Vision 2030 promotes the implementation of environmental-friendly industries that maximises ecological conservation, social and economic growth. The blueprint also advocates for inclusivity of public sectors, private entities, and citizens in engaging in sustainable development projects that focus on renewable energy, conservation of blue economy, and shift to sustainable consumption and production patterns (Government of the Republic of Kenya 2007).

The social pillar of Kenya's Vision 2030 that promotes economic empowerment and investment of people is a major step in initiating circular economy practices. The primary purpose of the social pillar is to improve the citizens' life quality to promote a clean and secure living setting. The social pillars create a platform for citizens to receive training on water and sanitation, environment, health, urbanisation, and gender inclusivity (Government of the Republic of Kenya 2007). The training occurs in Technical, Vocational Education, and Training (TVET) learning institutions. In the TVETS, leaners are trained to innovate practical activities to transform waste such as sawdust, scrap metals, and greywater into raw inputs for processing other usable products. In Kenya, TVETs are devolved to ensure there are circular innovations in every county and create a chance for a vast number of citizens to join the training.

Kenya's Vision 2030 also has an economic pillar that aims to achieve economic growth of 10% per year and maintain the rate until 2030 (Government of the Republic of Kenya 2007). Economic pillars allow the country to initiate circular economy practices such as empowering Community-Based Organisations (CBOs), women, youth, and vulnerable groups to engage in transforming plastic waste into horticultural crops trays, clothing fibres, building materials, and decorations (Government of the Republic of Kenya 2007). The ability of the CBOs and vulnerable groups to engage in income-generating activities boosts the Kenyan GDP as people can afford monetary resources to improve their living conditions. Waste recycling and transformation also play a significant role in reducing unemployment rates in the country and provide revenues to the government to kick-start development projects. Thus, the economic pillar of Vision 2030 allows the investment of circular economic activities to increase the disposable income of the citizens and boost economic growth.

Vision 2030 also presents the enablers and macro pillar that is cantered on constructing world-class infrastructural developments (Government of the Republic of Kenya 2007). The pillar will allow the construction of nine wastewater treatment facilities and nine solid waste collection and recycling plants in most Arid and Semi-Arid Lands (ASALs). Wastewater and solid plants will reduce the country's ecological footprint of generating and disposing of waste in the environment. The enablers and macro pillars also promote rain harvesting to improve water availability to the citizens.

Nationally Appropriate Mitigation Action (NAMA): Circular Economy Municipal Solid Waste Management Approach for Urban Areas-Kenya

This policy is commonly referred to as NAMA, whose primary purpose is to promote sustainable development, and reduce environmental and carbon footprints (Ministry of Environment and Natural Resources n.d.). NAMA policies incorporate technologies, financial resources, and private and public partnerships to invest in sustainable development practices. The Kenyan government implements NAMA regulations and recommendations through the United Nations Development Programme (UNDP). NAMA plays a critical role in promoting the waste value chain. The two main objectives of NAMA are the establishment of waste recycling infrastructures and partnerships between the public and private sectors to maximise waste recycling. Public and private partnerships will involve collaborations between the National Environment Management Authority (NEMA), Kenya Bureau of Standards (KEBS), Energy and Petroleum Regulatory Authority (EPRA), county governments, CBOs, waste collectors, and Non-Governmental Organizations (NGOs) (Ministry of Environment and Natural Resources n.d.).

Instead of completely disposing of waste in landfills and collection waste, NAMA plans to help Kenyan authorities to divert 90% of waste to the recycling facilities (Ministry of Environment and Natural Resources n.d.). NAMA policies and recommendations also aim to help the country to set up several waste recycling plants in urban areas to reduce littering and discharge of effluents into the environment. In the solid waste and wastewater treatment facilities, there is the production of organic fertilisers from the organic waste. The implementation of NAMA allows the establishment of small-scale and medium-scale recycling industries within Nairobi that helps to reduce the amount of waste disposal.

NAMA recommendations draw support from multilateral environmental agreements such as the Paris Climate Agreement to help Kenya reduce emissions of GHGs and initiate climate change mitigation measures. Kenya is a signatory to the United Nations Framework Convention on Climate Change. Thus, NAMA creates a platform for Kenya to shift to use generation of power from waste to reduce the use of fossil fuels that accelerates global warming and climate change.

4.5 Case Studies on Circular Economy Innovations

4.5.1 The Case Studies of Circular Economy in Africa Using Eastern and Central Africa, Southern Africa, West Africa, and Northern Africa

Over the years, African countries have been lagging behind industrial and economic growth (Andersen et al. 2021). Research indicates that between 2008 and 2011, the percentage of average job opportunities in African industries was 12.48% compared to Asia's at 22.48% (Andersen et al. 2021). However, in the recent past, there has been an increase in economic growth and industrialisation in the continent. Several African countries are facing a massive transformation in the agricultural sector, housing, and urbanisation. African governments and the AU are ratifying international multilateral environmental agreements such as the Paris Climate Agreement, the United Nations Convention on Biological Diversity (UNCBD), Basel Convention, and Agenda 21 of Rio Summits to develop practical activities to manage waste from rapid economic and industrial growth. Therefore, several African countries have initiated circular innovations to reduce disposable waste. This paper discusses examples of circular innovations from Eastern and Central Africa, Southern Africa, West Africa, and Northern Africa.

4.5.1.1 Mazzi Can in Tanzania

Mazzi Can is a high-quality plastic container that helps farmers in Tanzania store and transport milk (Becon 2016). A significant number of farmers in Tanzania use plastic bottles to transport milk to processing plants and customers. The use of plastic bottles presents an unhygienic condition of handling milk that increases the number of harmful microbes in milk. Using plastic bottles to transport milk also leads to the manufacture of single-use plastic packing materials to meet the high demand. Thus, the Tanzanian government, through a collaboration of Global Good Company and Bill and Melinda Gates Foundation, launched the Mazzi Can (Becon 2016). The Mazzi Can is a 10-l food-grade plastic material with a desirable opening to ensure easier packaging of milk and reduce the production of single-use plastic bottles used in milk transportation as shown in Fig. 4.2. Farmers in Tanzania supply milk to processing and buying centres using Mazzi Can and receive the container for reuse later. Yohannes (n.d.) highlights that Tanzanian researcher's highlight that the Mazzi Can plays a critical role in reducing harmful microbes in milk by over 76% and reduction of plastic bottle waste generation.

4.5.1.2 Construction Materials in Kenya

EcoPost is a private entity in Kenya that specialises in recycling plastic waste to produce construction materials (Koech and Munene 2020). The construction materials produced include plastic lumber used in fencing as shown in Fig. 4.3, among others such as tiles, plastic tables, and landscaping tools. EcoPost's plastic lumber is made of 100% recycled plastic waste. The company produces plastic

Fig. 4.2 Mazzi Can. (Source: Becon 2016)

Fig. 4.3 Fencing posts produced by EcoPost. (Source: EcoPost)

lumber posts of various colours such as black, brown, and grey, and a length of 15 ft. EcoPost states that there are no chemicals used in the production of plastic lumber.

EcoPost purchases plastic waste from various garbage collectors, women and youth recycling groups, learning institutions and collects plastic waste from major areas within Nairobi City County (Ronoh 2014). The company receives monetary and technical support from organisations like Coca-Cola, Bank of Africa, Safaricom Foundation, World Wildlife Fund (WWF), Bid Network, and Ocean Exchange. The construction materials made from plastic lumber are sold to Kenya Urban Roads Authority (KURA), Kenya Copyright Board, Pelican Signs, London Distillers and Urbanis Africa. EcoPost states that the production of construction materials has reduced deforestation of close to 250 acres of forests and diverted over one million kilograms of plastic waste from landfills to a recycling plant (Ronoh 2014).

4.5.1.3 Organic Waste Briquettes in the Democratic Republic of Congo (DRC)

The DRC continues to face rapid deforestation as people harvest trees for export and commercial activities (Sow et al. 2020). Local communities that reside near forest reserves illegally cut trees to extract firewood leading to the loss of endemic flora species. Sow et al. (2020) note that deforestation in DRC is threatening the existence of Bukavu and Kahuzi Biega Park. The continual use of charcoal and firewood is also causing an increase in respiratory diseases in the country. A private investor from DRC, Murhula Zigabe, has initiated a circular economy initiative of producing organic briquettes as alternatives to charcoal and firewood (Sow et al. 2020).

Zigabe's company, Briquette du Kivu, collects organic waste from banana peels, corn and beans remain, and sugarcane bagasse from households. Briquette du Kivu collects between 300 and 400 kg in a week from households and streets (Lauvergnier 2018). Once the waste is dried, it is subjected to a carbonised furnace for combustion to generate powdery substances. The powdery substance is then mixed with water to create a paste that dries to briquettes as shown in Fig. 4.4. Briduette du Kivu sells their products at a lower price of 50 Congolese francs to attract customers and reduce the usage of charcoal that drives deforestation and a high prevalence of respiratory illnesses (Lauvergnier 2018).

4.5.1.4 Organic Fertiliser Production in South Africa

South Africa produces large quantities of biomass from its vast agricultural activities (Batidzirai et al. 2016). The amount of biomass generated in South Africa has a

Fig. 4.4 Organic waste briquette making in the DRC. (Source: Lauvergnier 2018)

higher ability to support the generation of power and fertilisers. The country is developing a Bioenergy Atlas to increase investment in fertiliser production and energy generation from organic waste (Batidzirai et al. 2016). Increased investment in organic waste will reduce the production of inorganic fertilisers in South Africa that presents environmental problems such as soil leaching. South Africa is regarded as one of the major producers of inorganic fertilisers in the continent, with other countries like Nigeria, Libya, Tunisia, Algeria, and Morocco (AGRA 2019). The country aims to transform to the production of organic fertilisers that do not present adverse environmental and health consequences.

South Africa utilises food waste, animal manure, and other organic materials to produce fertilisers (Kido 2011). Kido (2011) states that the country has been using organic waste to produce fertilisers since 1969. Two per cent of organic waste from Cape Town and 15% of organic waste from Johannesburg are diverted to organic fertiliser processing industries (Kido 2011). The use of organic waste plays a significant role in reducing improper disposable of waste in most urban areas in South Africa. Using organic waste to produce fertilisers to produce reduces bad odour and helps to maintain the aesthetic value of ecological resources in the country. Organic waste also plays a critical role in the conservation of soil microbes that are used in the composition of organic waste (Ayilara et al. 2020). Several insects such as house flies, black soldier flies, and crickets are also mainly used to transform organic waste into organic fertilisers. Local municipalities in South Africa train farmers to avoid the slush and burn procedure of clearing farms but rather use vegetation to create organic fertilisers. The use of organic waste has been vital in improving the country's food security as there are high crop yields due to quality soils (Ayilara et al. 2020). Organic fertilisers promote an increase of soil nutrients, aeration, and maintenance of soil PH to increase crop production.

4.5.1.5 Waste Mobile Applications in Ghana

Ghana is experiencing rapid circular economy innovations to manage waste. In the country, there are several mobile phone applications that have been created and implemented to help individuals and organisations acquire waste management services. One of the mobile phone applications that are used to address waste in Ghana is *Jumeni* (Takouleu 2019). *Jumeni* mobile app is owned and operated by Jumeni Technologies. Jumeni mobile app helps households to pay for waste collection services using mobile banking technologies. The mobile app is compatible with several mobile phone models to create a platform for many Ghanaians to utilise in paying for waste collection services (Takouleu 2019). Jumeni also has a wide database of several waste collectors and recycling plants that help people to request their services to collect waste in their households. Jumeni also guides the waste collectors on key areas that require emergency waste collection to reduce the loss of aesthetic value of the ecological resources in the locality. The mobile applications create a chance for households to rate the services of the waste collectors to ensure that they perform their roles effectively. According to (Takouleu 2019), Jumeni is currently operating in Tema and Kaneshie municipalities.

The other mobile phone applications that are aiding sustainable management of waste in Ghana are CleanApp Ghana and COLIBA (Jackson 2016: Magoum 2020). The CleanApp Ghana was created and launched by Ghana Statistical Service (GSS) in November 2020 (Magoum 2020). GSS receives support from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) to operate the mobile application. The CleanApp Ghana allows the collection of waste on time for recycling. COLIBA is Ivory Coast-based but was launched in Ghana in February 2016 (Jackson 2016). COLIBA helps households to separate waste into plastics, metal, and organic for easier recycling. The mobile app allows households to receive a notification on planned waste collection dates or request waste collection services. Households that recycle waste through COLIBA receive points that they can redeem to purchase food, airtime, and other basic materials.

4.5.1.6 Hello Tractor Mobile App in Nigeria

Hello Tractor is a renowned technological firm that specialises in agricultural innovations (Goodier 2018). The company launched its mobile application, Hello tractor, to connect farmers to tractor services using the Internet of Things (IoT). Hello tractor was founded in Nigeria and operates in several African and Asian countries. Mobile applications play a critical role in helping farmers in Northern Nigeria to access mechanised farming practices that boost crop production (Otufodunrin n.d.). Research indicates that Africa has less than 50 tractors per 100 km^2 of agricultural land (Otufodunrin n.d.).

Hello Tractor reduces agricultural waste as weeds and other biomass materials in the farmland are ploughed with soils to boost organic content and fertility. Mixing organic content with soils reduces the use of inorganic fertilisers that cause soil leaching and air pollution, causing health complications to humans and fauna. Hello tractor allows providing a booking system that allows farmers to book and schedule tractor services. Farmers receive SMS notifications on planned data they will receive the services. Therefore, Hello tractor has been playing a major role in reducing agricultural waste in Northern Nigeria.

4.6 Barriers That Hinder Circular Economy in Africa

Agyemang et al. (2019) identified the unpredictable labour market and the high unemployment rate in Africa in their efforts towards the adoption of a circular economy. According to Akinade et al. (2020), the African continent is committed to the adoption of circular business models, especially in its future planning. The development of infrastructure and resource use is performed with the focus on the future to improve sustainability and minimal ecological footprint. Similar views by De-Jesus and Mendonça (2018) indicated that Africa has embraced a circular economy with the objective of ensuring affordability of its implemented projects and high-level eco-friendliness, hence, contributing towards the improving productivity of the critical natural capital. In the same way, the focus on improving job availability to the Millions of Africans has driven countries to consider the adoption of sustainable approaches that engage the informal economy. However, the high rate of unemployment has led to comprise of unsustainable practices in some private and public institutions, hindering circular economy growth in Africa.

Kerdlap et al. (2019) noted the variations in institutional capacity to implement the circular economy strategies, as the main contributor towards the underdevelopment and the high fragmentation levels within the private sector. The heavy investment required by the growing economy to improve their infrastructure and the general urbanisation is associated with heavy financial burdens that are difficult to main. Similarly, De-Oliveira et al. (2019) established that the active informal economy lying beyond market interventions takes a huge portion within Africa, making it challenging to implement the appropriate circular economy approaches. Kinnunen and Kaksonen (2019) found that the priorities of African countries have led to struggles towards growing sustainability in the area without sufficient investment into the key sustainable areas of recycling, repairing, and reusing the raw materials within the industry. Consequently, most regional trade policies and the various investment programs have faced the challenges of actual investment into sustainable practices due to insufficient capacity. Therefore, the implementation of programs to support the successful integration of green economy practices in Africa must focus upon the establishment of systems to support institutional capacity, which acts as a platform for the execution of sustainable plans. However, De-Oliveira et al. (2019) that empowerment and general institutional capacity building play a critical role in supporting the African circular economy but are associated with huge financial requirements that act as a barrier to the process.

The lack of sufficient national support and willingness to adopt change by African leaders is lowering the rate of adoption of a circular economy. De-Jesus and Mendonça (2018) identified World Economic Forum as one of the institutions on the frontline towards transforming Africa's circular economy with the main goal for delivering economic growth, creation of job opportunities, and the protection of the environment. The institution advocates for the project implementations that can deliver the highest value of the resources and ensure reusability is attained. Generally, WEF is playing a critical part in transforming Africa into a circular economy to deliver jobs for youths, overall economic growth, along positive environmental outcomes. However, Ki et al. (2020) revealed that Africa's chances to shift into circular economic patterns are higher as opposed to other continents where the vast infrastructure was put up without projecting on the next life cycles. The continent has good potential of moving into a circular economic model because its ecological footprint is still low (De-Oliveira et al. 2019). The introduction of a circular economy in the continent has assisted in preserving the production capacity of the critical natural resources, expansion of employment capacity in the informal economy, and inspiring proper investment policies in the region. Despite the fact that the envisioned positive impacts of WEF, Kinnunen and Kaksonen (2019) confirmed that most leadership teams of the African countries are providing sufficient support, leading to reduced adoption of a circular economy.

According to Berg et al. (2018), Africa has received financial and other forms of support to foster a circular economy but faced the challenge of poor planning and resource utilisation. The adoption of circular economy in Africa materialised after the launching of the African Circular Economic Alliance (ACEA) in 2017 when the Rwandan government spearheaded the partnership with WEF (Charles et al. 2019). The primary goal of constituting the ACEA was to carry out policy research and promote high-impact circular economic-related projects; this alliance has more than ten member states from the continent, co-chaired by environment state ministers from South Africa, Rwanda, and Nigeria (Ghisellini et al. 2016). The launching of ACEA has attracted a multi-donor trust funding from global investors with an initial donation of about $4 million, where funding of circular economic projects and entrepreneurs from member states is enforced through the African Circular Economic Support Program (ACESP) (Ghisellini et al. 2016). Owolabi explained that adopting a circular economy in Africa has assisted most member countries to utilise their resources to the highest value and recycle waste materials to useful products, hence, yielding the maximum value out of them. However, despite the benefits and support for circular economy received from donors, poor planning and misappropriation of funds remain some of the key challenges towards the implementation process.

Agyemang et al. (2019) noted that with the high reliance of the developing economy on the extractive industries, there are many forms of resistance from the public and private sector on adopting the circular models that affect the value chains and the secondary material use. Resistance has negative impacts on the success of the circular economy models since lack of support reduces their speed of implementation and increases the chances of failure within the economy. Schroder et al. (2019a, b) added that the specific interests of people and the general stakeholders' attitudes have affected the process of adopting a circular economy within Africa. However, Charles et al. (2019) argued that the determination and interest of the national leadership among the individual African countries affect their level of success in the integration of circular economy since they can formulate policies and guidelines to support the adoption of the models. Therefore, the ability of the government to manage the specific industry interests that deter the implementation of the circular economy increases the chances of success in the execution process.

Gazzola et al. (2020) identified the capacity and the financial constraints as the challenges of the main elements facing circular economy implantation in Africa. The institutional capacity has limited the efforts to establish and enforce the appropriate regulations and standards for circular activities. As a result, some countries have failed to adopt string governance frameworks, leading to risks of installation of cheap and limited-quality technological systems and equipment. The design and implementation of substandard projects within different sectors of the developing countries in Africa have led to increased chances of compromise to the expected standards of the circular economy.

Similarly, De-Jesus and Mendonça (2018) noted that the limited access to finance by most African countries is a key challenge towards their execution of circular economy activities. With the huge financial implication involved in shifting the infrastructure, industry processes, and priorities for creativity and innovation, the lack of budgetary support affects their general success. Availability of funding increases the success of the circular economy approaches and the general adoption level of the best practices. In contrast, Fontana et al. (2021) argued that the appropriateness of the circular economy project implementation plan is the key determinant to the success access of funds because attractive solutions always win sponsors and investors into African countries. Therefore, the accessibility to the funds improves the implementation process of the circular economy through financing the required activities.

The recommendations of Cecchin et al. (2020) indicate that the increased accessibility to the right technological solutions can increase the effectiveness of the circular economy models in Africa. Some technologies such as satellite-based Global Positioning System (GPS), Internet of Things (IoT), Artificial Intelligence (AI), and block chain technologies have contributed towards the transformation of different countries to promote compliance. As a result, with the utilisation of technologies, organisations can conduct different business activities with regard to environmental protection and sustainability factors. However, Gazzola et al. (2020) argued that despite the rise and access to the best global tech solutions, the technological, infrastructural platforms are still ineffective in most parts of the country. The unavailability of the internet in some parts of Africa limits the adoption of technology for supporting the circular economy.

According to Fontana et al. (2021), the circular economy and smart building designs have helped Africa to increase its ability to maintain buildings with efficient services throughout the lifespan. The connectivity, intelligent machines, embedded sensors, and data analytics systems provide efficiency and cost-saving, hence, improving the benefits of a circular economy. Ki et al. (2020) noted that reuse, resell, repair, refurbish, and remanufacturing are the key circular economy practices that are being applied in resource utilisation within Africa. In the process, the circular supplies of the raw materials must be supplied to enhance the renewability, recyclability, and biodegradeability of the inputs. Similarly, Fontana et al. (2021) noted that the circularity of the natural resources in Africa is essential for sustainability and the general supply within their economy, hence, helping to reduce emissions, create jobs, and strengthen the national energy securities. However, Fontana et al. (2021) noted that resource recovery should be the key consideration in Africa through the formulation of technological business models that support innovations for recovery and the reuse of the resources. Consequently, a circular economy will enhance the maximisation of economic value and the elimination of material leakages. Agyemang et al. (2019) identified the extension of the product lifecycle of the products as important in ensuring economic re-use through upgrades, re-market, remanufacture, and repairs. Therefore, the adoption of diverse strategies with the main goals of ensuring that the resources are efficiently used helps to improve the circular in Africa.

Ki et al. (2020) stated that insufficient and ineffective sharing platforms across Africa have reduced their ability to create connections and interactions for the improvement of resource sharing towards building a circular economy. Essentially, the products and assets that provide low ownership rates foster productivity and create value for both the nations in general through improved logistical processes.

Similarly, Cecchin et al. (2020) stated that the shared platforms facilitate the product as service models that allow customers to lease or make pay-for-use arrangements that promote a buy-to-own economy. As a result, companies can manage to reduce the operational costs and upfront requirements for the acquiring of the resources for the company use. Reduced operational and maintenance cost allows recapturing of the residual value, which motivates the companies to make indirect support for the circular economy (Fontana et al. 2021). Therefore, the lack of sufficient sharing systems within Africa has reduced the ability of nations to interact, hence, reducing the effectiveness of the implementation of a circular economy.

The high people population in Africa has created limitations towards the implementation of a circular economy. According to Fontana et al. (2021), the United Nations Population Fund (UNPF) estimated that there are over 200 million people in Africa below 25 years, this number is predicted to double by 2045, and if this happens, the adequate demographic ground will be set for fast-growing economy provided the available economic resources are well utilised to create enough job opportunities. Ki et al. (2020) showed that an environmental protection agency from the United States estimated that recycling about 10,000 tons of used products can create six times more jobs than the original use; reusing and repair can create even more opportunities to be occupied by the anticipated population growth. Besides creating employment opportunities, Gazzola et al. (2020) identified that circular economy has also played a significant role in aiding sustainable economic development across Africa, with more relevant research being pursued. For this reason, the circular economy has revived the recycling industry in the continent, which has reduced wastes and created more jobs for growing populations (Fontana et al. 2021). A circular economy can create new livelihood opportunities for disadvantaged groups to stay in a clean environment, with the reduced flow of plastic waste into the marine atmosphere.

4.7 Recommendations

This study recommends the following recommendations:

- Embracing CE in solid waste management requires deliberate efforts in integrating the managers/stakeholders together to close the loop where wastes become raw materials for another activity.
- African countries' financial support to medium-scale and small-scale enterprises that specialise in various circular economy initiatives like waste recycling, among others
- Enactment of adequate circular economies for each sector such as agricultural, transportation, manufacturing, and educational training to ensure effective implementation of circular economy practices.
- Effective enforcement of circular economy policies and initiatives through legal authorities such as policing units to ensure an increased shift from a linear economy to a circular economy.

- Incorporation of circular economy ideas into learning institutions' training curriculum to create increased awareness on the importance of waste generation, renewable energy, and environmental-friendly agricultural practices.
- Increased investment in Information, Communication, and Technologies (ICT) to create increased wireless connectivity and wider utilisation of smart technologies to promote crowdsourcing of skilled experts to initiate circular economy innovations.
- Increased purchase of products from circular economy practices by governments to create an active market to attract increased investments.

4.8 Conclusion

CE has been used in Africa for several years. The main countries in Africa that are driving CE are Nigeria, South Africa, Rwanda, Ethiopia, Tanzania, DRC, Mauritius, Egypt, Namibia, Ghana, and Kenya. A significant number of African countries are facing increasing urbanisation. Research indicates that most cities in the continent will transition to megacities. Increased urbanisation will lead to a significant increase in waste generation. Thus, most African countries have recognised the need to shift from linear economy to circular economy to promote environmental, economic, and social pillars of sustainability. A circular economy will help African countries to reduce their carbon and ecological footprints due to the use of waste as a substitute for raw materials and reduced dependence on fossil fuels. Networks such as the African Circular Economy Alliance (development of national and local government policy) and the Africa Circular Economy Network (strategic application in business) working in collaboration will be able to facilitate this transition process. Several African countries have started initiatives to strengthen their political system to enact circular economy policies. Some countries are also updating their existing sustainable policies to incorporate circular economy aspects. Regional organisations like the African Development Bank (AFDB), African Union (AU), and international organisations like the United Nations, World Bank, UNEP, UNIDO, UNDP, and GIZ are helping African countries to ratify their circular economy-related practices into practical innovations.

Circular economy innovations in Africa include the use of organic waste to generate fertilisers in countries like South Africa. Organic fertilisers play a significant role in reducing the use of inorganic agricultural inputs that cause soil leaching, soil contamination, and air pollution. The use of organic waste reduces the amount of waste that is disposed at landfills and dumpsites that cause environmental challenges such as increased methane emissions that accelerate ozone depletion. The other circular innovation in African countries like Ghana and Nigeria is the use of mobile applications to manage waste. Mobile applications help people to request waste collection services from waste collectors and waste recycling plants. The mobile applications are compatible with several mobile phone models to ensure that a significant number of people use the technologies. In Kenya, there is the use of plastic waste to produce construction materials like poles. Plastic construction materials are durable and reduce littering of the environment with plastic bottles. In African countries like DRC, there are small-scale circular economy initiatives like the production of briquettes from organic waste. Organic briquettes help to reduce deforestation that is threatening forest reserves. In Tanzania, there is the utilisation of Mazzi Can to reduce the generation of single-use plastic bottles for milk transportation. In conclusion, African countries will enhance the achievement of their Sustainable Development Goals by fully embracing Circular Economy policies and innovations.

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5 Waste Management in Indonesia: Strategies and Implementation of Sustainable Development Goals (SDGs) and Circular Economy

Arisman and Yun Arifatul Fatimah

Abstract

Indonesia faces significant challenges in waste management, with plastic pollution being a major concern. Implementing circular economy principles, such as promoting recycling, reuse, and reduction of single-use plastics, can help manage waste effectively and reduce the carbon emissions associated with waste incineration and landfilling. By adopting circular economy practices, Indonesia can work toward decarbonization by mitigating the environmental impact of waste and reducing greenhouse gas emissions. The objectives of this article include discussing the potential of implementing circular economy and circular economy technology adopts in Indonesia to achieve SDGs and its contribution to the decarbonization efforts to mitigate climate change. Circular economy technology adopts in Indonesia is usually driven by the situation in different cities—not vice versa. The adoption of technologies is justified by the situation in the cities that offer a new system to meet the city's requirements.

Keywords

Circular economy · Decarbonization · Extended producer responsibility · CE technology · Waste management

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5.1 Introduction

The idea of a circular economy has its roots in industrial ecology, which explains the industrial economy and its processes as a human ecosystem. It involves the industrial system along the lines of an ecosystem, recognizing the efficiency of resource cycling in the natural environment. The circular economy is almost making modern esteem chains that decouple development from the utilize of rare and direct asset inputs. For occurrence, a company seems to advance utilizing “lasting” assets to break the connect between shortage and financial movement by utilizing as it were inputs that can be ceaselessly reused, reprocessed, or re-established for beneficial utilize (e.g., renewable vitality, biomaterials, or completely recycled/recyclable assets).

> Circular economy is a systems-level approach to economic development and a paradigm shift from the traditional concept of linear economy model of extract-produce-consume-dispose-deplete (epcd2) to an elevated echelon of achieving zero waste by resource conservation through the changed concept of design of production processes and materials selection for higher life cycle, conservation of all kinds of resources, material and/or energy recovery all through the processes, and at the end of the life cycle for a specific use of the product will be still fit to be utilized as the input materials to a new production process in the value chain with a close loop materials cycle that improves resource efficiency, resource productivity, benefit businesses and the society, creates employment opportunities and provides environmental sustainability (Ghosh 2020).

The significant increment in Indonesia’s populace has expanded the volume of squander. Besides, the utilization design within the community has altogether contributed to the generation of different squander such as squander with dangerous packaging and/or squander that don’t effectively break down by normal handle. So distant, the individuals still consider squander as unusable remainders, not as advantageous assets. In squander administration, the community still depends on the end-of-pipe approach, i.e., squander is collected, transported to, and arranged at the ultimate squander preparing. The end-of-pipe approach to squander administration ought to be changed by an unused worldview of squander administration. The new worldview considers squander to have financial esteem and may be used as vitality, compost, compost, or mechanical crude fabric. Squander administration is carried out comprehensively: from the upstream, sometime recently an item possibly gets to be squander, to the downstream or the organize where items are utilized to create squander and would return to the environment safely.

The concept of a circular economy is embraced for its potential to create jobs and future-proof economic growth, increase private sector investment and profits, improve the standard of living, and decrease the negative impact on environment, nature, and climate. As an example, the introduction of Circular Economy principles within the European Union is estimated to increase GDP in the EU by 7% points (by 2030) and improve the disposable income of households by up to 11% points compared to the linear “business as usual” model. European countries like Denmark, Finland, France, Belgium, and the Netherlands have outlined their circular economy policies and strategies, expecting specific economic benefits (job creation, more competitive business environment and improved market value, investments in new technologies, improvement of the trade balance, reduction of primary material consumption). Beyond Europe, countries like China and India have introduced circular economy roadmaps and Brazil is developing a circular economy strategy. These countries are at widely differing economic starting points. But they all share the conviction that a circular economy will bring economic benefits beyond today's take-make-dispose model.

The objectives of this article include discussing the potential of implementing circular economy and circular economy technology adopts in Indonesia to achieve SDGs and its contribution to the decarbonization efforts to mitigate climate change.

5.1.1 Circular Economy and Decarbonization

Circular economy and decarbonization are interconnected concepts that complement each other in achieving sustainability and mitigating climate change. Circular economy strategies can help reduce carbon emissions by optimizing resource and energy use, minimizing waste, and promoting sustainable consumption patterns, thereby contributing to decarbonization efforts. The relationship between circular economy and decarbonization in Indonesia is significant as the country faces environmental challenges and is committed to addressing climate change.

Here are some key aspects of their relationship in the Indonesian context: (1) Waste Management: Indonesia faces significant challenges in waste management, with plastic pollution being a major concern. Implementing circular economy principles, such as promoting recycling, reuse, and reduction of single-use plastics, can help manage waste effectively and reduce the carbon emissions associated with waste incineration and landfilling. By adopting circular economy practices, Indonesia can work toward decarbonization by mitigating the environmental impact of waste and reducing greenhouse gas emissions. (2) Sustainable Agriculture and Forestry: Indonesia's economy relies heavily on agriculture and forestry, which can contribute to deforestation, land degradation, and carbon emissions. Circular economy approaches, such as sustainable and regenerative agriculture practices, can help optimize resource use, reduce waste, and promote biodiversity conservation, which can contribute to decarbonization efforts by mitigating deforestation and promoting sustainable land management practices. (3) Renewable Energy: Indonesia has vast renewable energy potential, including solar, wind, and hydropower. Emphasizing the adoption of renewable energy sources and promoting energy efficiency through circular economy principles can help reduce reliance on fossil fuels and lower carbon emissions. Indonesia has set targets for renewable energy expansion, and circular economy approaches can support the country's efforts toward decarbonization by promoting renewable energy adoption and reducing greenhouse gas emissions from energy production. (4) Sustainable Transportation: Transportation is a significant source of carbon emissions in Indonesia. Implementing circular economy principles in the transportation sector, such as promoting public transportation, car-sharing, and electric mobility, can help optimize resource use, reduce waste, and lower carbon emissions. Circular economy approaches in transportation can support Indonesia's decarbonization efforts by promoting sustainable mobility and reducing greenhouse gas emissions from transportation activities. (5) Circular Business Models: Circular economy can also spur innovation and create new business opportunities. Emphasizing circular business models, such as product-as-a-service, remanufacturing, and circular supply chains, can help Indonesian businesses adopt sustainable and resource-efficient practices, which can contribute to decarbonization efforts by reducing resource consumption, waste generation, and carbon emissions.

5.1.2 Strategies in Indonesia Toward Circular Economy

Indonesia has for the past decade experienced an impressive economic development lifting millions of people out of poverty and elevating it to becoming a middle-income country. However, the negative consequences of the economic growth also start to show, hampering climate and the environment, nature and health and the perspectives for future continued growth. Problems are emerging with air pollution and water quality, shrinking of forest cover, pressure on biodiversity, haphazard urbanization, depletion of fisheries, and high levels of waste generation and plastic leakage to the environment generally and ocean in particular. This in turn threatens local economies and food production as well as tourism potential. These problems will intensify in the future if the current growth paradigm is not changed.

The Government of Indonesia has already reacted to this challenge and adopted various ambitious policies, plans, and strategies to pursue a sustainable development track. The Government has shown strong commitment to the SDGs including issuing the Presidential Decree no 59/2017 on SDG implementation, and linking the SDGs to the current Medium-Term Development Plan (RJPMN) 2015–2019 and the pending RJPMN 2020–2024. On climate change, the Indonesian Nationality Determined Contribution (NDC) to the Paris Agreement and the NDC implementation strategy (2017) show a similar determination by the Indonesian Government to ambitious actions. And within waste handling—which is especially relevant to the development of a circular economy—the Law 18/2008 on Solid Waste Management based on the 3R principles, the Presidential Decree 83/2018 on Marine Debris Management, and the Presidential Regulation 18/2016 on Waste-based Power Plant Acceleration are all timely and excellent examples of governments' commitment to sustainable development. The circular economy is believed to be an important solution to achieve the SDGs by 2030, including Goal 6 on clean water and proper sanitation, Goal 8 on economic growth, Goal 11 on sustainable cities, Goal 12 on sustainable consumption and production, Goal 13 on climate change, Goal 14 on marine ecosystems, and Goal 15 on terrestrial ecosystems. The circular economy agenda is also included in the National Medium-Term Development Plan (RPJMN) 2020–2024 as part of the low-carbon development strategy. The target is to reduce greenhouse gas emissions by 29–41% by 2030. Through low-carbon initiatives and implementation, we hope to achieve growth potential by maintaining low-emission activities in cities. Indonesia is committed to preserving nature while maintaining economic growth.

Transition to a circular economy requires the public and private sectors to walk hand in hand. The government will provide the enabling framework, and the private sector will be the engine driving the circular economy forward. Consequently, the project of establishing a National CE Strategy requires commitment and active participation by both the Indonesian government and the Private sector in a true Public Private Partnership.

The government will play a central role in bringing a circular economy into existence in Indonesia and engaging with stakeholders from all societal forces outside the government (industry/business, civil society, academia) and defining new business models and Circular Economy opportunities. Experience in other geographies has demonstrated that a wide-ranging consultation and engagement with various actors is fundamental to create ownership for the required change and channel the commitment and energy of all partners involved. The Sustainable Development Goals (SDGs) are closely related to the circular economy, especially goal no. 12, namely Responsible Consumption and Production. “Indonesia has prepared a framework for agenda no. 12 SDGs, namely the implementation of Sustainable Consumption and Production (SCP) which is currently entering the acceleration stage, namely SCP encouraging resource efficiency, low-carbon development strategy, green economy, circular economy”. There are the four strategies implemented are: Green Public Procurement and improvement of environmentally friendly public facilities; supply drivers: portfolio of new products/services/investments that are environmentally friendly, “sustainable sourcing”, innovation, “green technology”, “sustainable financing”; “Resource pools”; SCP’s concrete action menu platform for government, business, and society; creation of new job/economic potential through integrated waste management services, utilization of rainwater, and others.

Circular economy is one way to reduce the burden on the environment. The Ministry of Environment and Forestry also has a target for Indonesia to be free from waste by 2025 based on a circular economy system. The application of a circular economy must also start from upstream, where producers make products from materials that can be reused. The implementation of a circular economy can generate significant economic, environmental, and social benefits by 2030. This model has the potential to generate additional GDP of Rp593 to Rp. IDR 638 trillion, reducing waste per sector by 18–52%, and creating 4.4 million new jobs, of which three quarters will empower women with better opportunities by 2030. In several studies and scenarios of applying the circular economy principle, if we start now in the five priority sectors, then by 2030 this circular economy can reduce CO_2 emissions by up to 126 million tons, and save water usage by up to 6.3 billion cubic meters.

5.2 Plastic Waste Management in Indonesia

Indonesia is ranked the second largest plastic waste producer in the world after China. Based on data from the Ministry of Environment and Forestry (KLHK), it shows that the amount of landfill in Indonesia reaches 67 million tons per year. Based on the data from the SIPSN (Information System of National Waste Management) in 2018, the major source of waste production are organic waste from household 42.22% and the composition of plastic waste in Indonesia is 10.58%. Figure 5.1 shows the municipal waste composition in Indonesia.

From the total national waste 3.2 million tons of which is plastic waste dumped into the sea. This means that every resident of the Indonesian coast is responsible for 17.2 kg of plastic waste floating and poisoning marine animals. Meanwhile, ten billion plastic bags are disposed of into the environment per year or as many as 85,000 tons of plastic bags. Meanwhile, waste production in Jakarta reaches 6500 tons per day and 13% of this waste is plastic waste. In Bali, the figure reached 10,725 tons per day, while in Palembang, the figure rose sharply from 700 tons per day to 1200 tons per day. Figure 5.2 shows the non-collected waste and collected waste in Indonesia.

The number of plastic waste imports from other countries in 2018 reached 320,000 tons, an increase of up to 150% from the previous year. The impact, of course, is that pollution in Indonesia will increase and the quality of the environment will be threatened. Plastic waste actually has great potential to be recycled. Referring

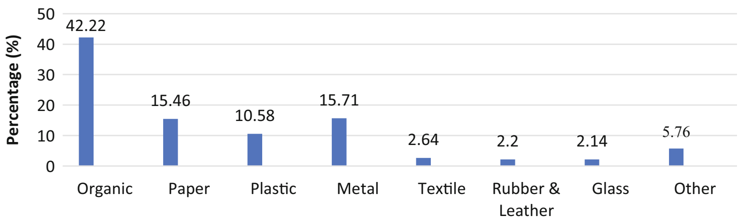

Fig. 5.1 Municipal waste composition in Indonesia

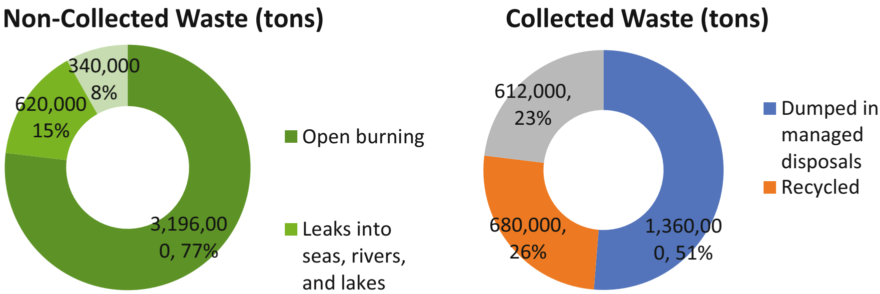

Fig. 5.2 The percentage of non-collected waste and collected waste in Indonesia

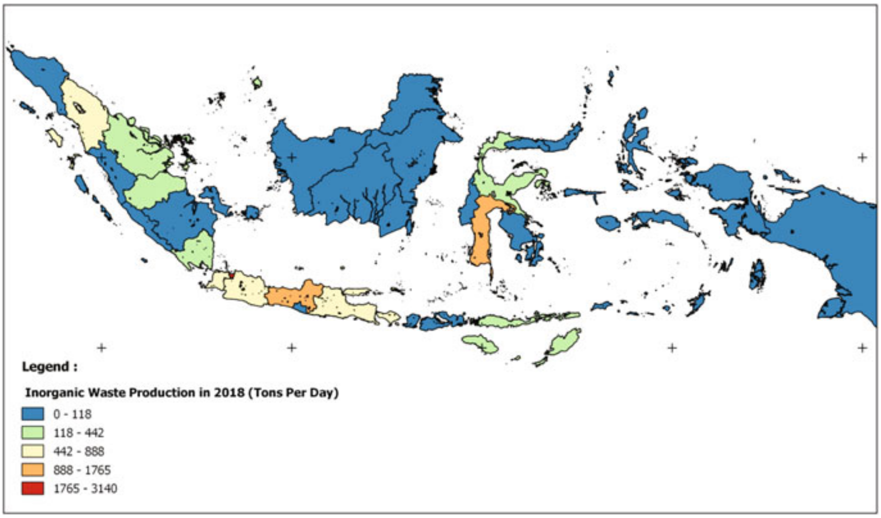

Fig. 5.3 Non-organic waste production in Indonesia

to data from Inaplas, of the 2.7 million tons of plastic waste, only about 61.5% has been recycled. Therefore, it is very important to reduce plastic waste to the surrounding environment with access to household waste services in urban, suburban areas and islands.

Figure 5.3 shows the non-organic waste production in Indonesia. Based on research by the University of Georgia, an estimated 3.22 million metric tons of plastic waste is tossed annually into the ocean surrounding Indonesia, while another 8.82 million metric tons of China's plastic waste also makes its way into the ocean. The crisis of plastic waste isn't just limited to the ocean, but it has also affected Indonesian rivers. Data from Nature Communications revealed that four of Indonesia's rivers such as Brantas, Solo, Serayu, and Progo rivers rank among the 20 most polluted rivers in the world. The plastic waste choking rivers deprive local communities of their source of food and water. Clogged rivers also increase the likelihood of flooding which would be damaging to the surrounding communities.

Most of the plastics in Indonesia are not recyclable and do not biodegrade naturally, so plastic usually ends up in landfills. The largest landfill in Indonesia is the Bantar Gebang TPA in Jakarta. More than 900 trucks operate there and deliver more than 5000 tons of solid waste every day. These landfills can be dangerous for the environment because plastic waste also releases harmful chemicals into the atmosphere. Initially, landfills pollute the air as chemicals seep into the ground and eventually flow into rivers and lakes. Landfills also emit methane gas which is known to contribute to air pollution.

From the complex problem of plastic waste, the Indonesian government also teamed up with the Global Plastic Action Partnership (GPAP), an international public-private collaboration plans a target of reducing plastic waste in the ocean by 70% by 2025 while considering the economy and people's lives. The Indonesian government and GPAP are implementing strategies such as collecting local waste management data and building models that evaluate solutions such as reducing over packing, making new plastics recyclable, and increasing recycling and waste collection rates. In addition, the model will calculate the required investment, timeline, environmental footprint and greenhouse gas emissions, and their impact on people's lives. To achieve this target, the government says it will contribute US$ 1 billion per year to this effort.

5.3 Circular Economy Implementation: Priority of Industry Sectors in Indonesia

5.3.1 Food and Beverage (Focus on Food Loss and Waste)

The Indonesian food & beverage (F&B) sector accounted for 9.3% of the total GDP in 2019, making it the largest sub-sector of the manufacturing sector on that year. Thus, this sector is highly relevant to drive a circular economy transformation.

There is an urgent need for a circular economy transformation in the food production system. World Resources Institute analyzed that, around 26% of all food available is wasted every year in South and Southeast Asia. In Southeast Asia, most of the 65% food loss and waste occurs during the production or the handling & storage stage of the value chain. In these two stages, unscheduled harvesting due to a lack of weather data and improper storage are examples of waste generation drivers. Improper transportation logistics and customer behavior, respectively, are drivers of waste in the supply chain and consumption stages. Food loss and waste affect a wide range of food items in Indonesia, including grains, fruits, and vegetables. According to the Association of Indonesian Chilli Agribusiness, 15% of chilies arrive in Indonesia spoilt or too dry for Indonesian palates.

A circular economy can not only help to prevent food loss and waste (e.g., by shortening supply chains), but it can also help to redirect food loss and waste to more beneficial uses, such as composting and biogas production. Increased agrobiodiversity can be achieved by more localized value chains and regenerative agriculture. Other countries have seen the F&B scheme as a huge opportunity. By 2030, the overall potential to reduce food waste in the European Union is estimated to be around USD320 billion. Excessive use of fertilizers, pesticides, and antibiotics in food processing, as well as excessive use of freshwater resources, high energy use, and inadequate and unhealthy disposal of organic by-products, all contribute to substantial negative externalities both environmentally and socially. These negative externalities are estimated to be worth USD5.7 trillion globally. Improving farming practices, eliminating waste and contaminants from the food supply chain, and maximizing all nutrients could have major economic, social, and environmental benefits.

5.3.2 Textiles (Focus on Textile Waste)

The textiles industry is a major source of jobs and exports in Indonesia, and it is also a key priority of the government's potential export strategy. The sector employs approximately 4.2 million workers, accounting for over 26% of all manufacturing jobs in Indonesia. Indonesia is one of the world's top ten textile-producing countries. Despite a global decline in textile demand, the Indonesian textile industry is projected to expand at a rate of 5.7% per year from 2018 to 2024. By 2030, the Indonesian government wants to raise the volume of textile and garment exports to USD75 billion.

Textile production has an environmental effect across the supply chain, with the dyeing and finishing processes having the greatest impact because they are the most energy, water, and chemically intensive. To produce finished fabrics, all types of fabrics usually go through a wet processing phase that includes washing, bleaching, dyeing, and finishing. This phase of the wet processing process uses a lot of freshwater and releases a lot of potentially toxic substances. Indonesia has attempted to solve this issue by introducing the "Standar Industri Hijau (SIH)," a voluntary sustainability standard for the textile industry (Green Industrial Standard). The norm aims to reduce the use of raw materials and hazardous chemical emissions.

The SIH could serve as a springboard for transforming Indonesia's textile industry. Circularity in clothing and footwear, however, must extend beyond the manufacturing process. According to the Ellen MacArthur Foundation, the global textile manufacturing system loses USD500 billion in value due to under-utilized clothing and a lack of recycling. As much as 87% of the total fiber production used in clothing is landfilled or incinerated, resulting in a loss of more than USD100 billion per year. Less than 1% of the material used in the production of clothing is recycled into new garments. As a result, textile waste recycling may be a profitable sector. Textile waste is recycled in Panipat, India, to make various textile items such as doormats and blankets. It is considered the global hub for textile recycling. It has 20,000 employees and generates USD62 million in annual sales.

A circular economy in textile manufacturing will benefit the Indonesian economy in a number of ways, which include material cost savings and reduced exposure to input resource price fluctuations, profit opportunities for companies through new services (fashion-as-a-service), and increased economic development through a more regenerative and restorative supply chain. Lower GHG emissions, reduced consumption of virgin, non-renewable resources, and reduced energy consumption are only a few of the environmental benefits.

5.3.3 Construction and Built Environment (Focus on C&D Waste)

Infrastructure is the bedrock of urban and rural growth, poverty reduction, and increased access to public services. The construction sector in Indonesia accounts for 10% of total GDP and is expected to expand rapidly in the future due to factors such as urbanization. Construction and infrastructure use a lot of electricity and use a lot of clean water. Infrastructure building and maintenance account for roughly 40% of a country's energy expenditure globally. It can also be a major source of solid waste and has a high recycling potential. Nearly all C&D waste is recyclable, but in developing countries like Indonesia, only one to 15% of the waste is expected to be recycled. The current linear economic model has resulted in an industry with minimal and restricted innovation, under-utilization of key assets, and substantial waste of materials and resources. Indonesia has already started introducing energy and water conservation standards in Jakarta and other cities, thanks to the Green Building Council Indonesia. However, "greening" current infrastructure is both difficult and inadequate. To eliminate the system's inefficiencies, a more systematic approach is needed. The building and real estate industries usually deliver one of the highest potentials, according to European experience with circular economy approaches. The importance of unlocking the circular economy in the built environment in Denmark has been estimated to be between EUR0.85 and 1.2 billion per year. By 2022, the green building market in India is projected to expand to USD35–50 billion.

5.3.4 Wholesale and Retail Trade (Focus on Plastic Packaging Waste)

For Indonesia, plastic waste has become a huge problem. Indonesia produces 6.8 million tons of plastic waste per year, which is expected to increase to 13.6 million tons by 2040. Just 30% of Indonesia's plastic waste was treated in 2017 (10% was recycled and 20% was sent for managed disposal). The remaining 70% was either burned freely, discarded on land, transported to official dumpsites, or leaked into the ocean or waterways.

Indonesia is thought to be responsible for 10% of global ocean plastic leakage. By 2025, the Indonesian government has committed to reducing marine plastic debris by 70%. As a result, it began programs to eliminate plastic waste and move away from end-of-pipe recycling to a circular economy model. The Coordinating Ministry for Maritime Affairs and Investment and the Ministry of Environment and Forestry, in particular, have partnered with the Global Plastic Action Partnership (GPAP) to develop circular economy solutions in coastal areas where plastic waste is an issue. The potential for economic growth is immense. According to the World Economic Forum, achieving near-zero plastic emissions by 2030 could result in 150,000 direct jobs and a USD13.3 billion investment potential in Indonesia between 2025 and 2040.

5.3.5 Electrical and Electronic Equipment (Focus on e-Waste)

In Indonesia, the electrical and electronic equipment industry (also known as the electronics sector) is a key potential region for circular economy initiatives. Metals, computers, optical instruments, and electronics manufacturing contributed 1.9% to

Fig. 5.4 The potential of circular economy in reducing waste

Indonesia's GDP in 2019. According to estimates, Indonesia has the fourth-largest smartphone user population and the third-largest mobile internet user population in the world, with 78 million and 65.2 million users, respectively. The government designated the electronics industry as one of the main sectors in April 2018 as part of Indonesia's overall industrial growth strategy.

In the electrical and computer equipment market, the economic potential of a circular economy is important. A standard iPhone is estimated to contain 0.034 g of gold, 0.34 g of silver, 0.015 g of palladium, and less than a gram of platinum. Only the global economic potential of a more intelligent, circular looping of smartphones and their materials alone could be worth more than USD11 billion per year. Tiny, unorganized players dominate the electronic product reuse and recycling market in Indonesia. Upskilling of informal staff in the e-waste recovery and recycling sector could significantly increase the economic value of end-of-life electronic goods and e-waste.

A circular economy may also have a positive impact on the climate. Rare earth metal mining, which is used in the manufacture of electronic and electrical devices, may have a negative effect on the environment. One ton of rare earth elements produces 2000 tons of radioactive waste which takes a lot of energy to process. Furthermore, the disposal of electronics can result in toxic chemicals leaking into the atmosphere. Circular business models that rely on the reuse, refurbishment, and recycling of electrical and computer equipment can help to minimize the usage of natural resources while still avoiding negative environmental consequences.

Figure 5.4 Shows the potential of Circular Economy in Reducing Waste. Five key areas of the Indonesian economy with high potential for circularity that can solve many of Indonesia's problems. Fig. 5.5 explains the potential for circularity to solve the problem.

5.4 Extended Producer Responsibility (EPR) Implementation and Plastic Waste in Indonesia

Several producers have started to voluntarily implement EPR practices in an effort to reduce and manage plastic waste from their products or packaging.

5.4.1 EPR Implementation for the Reduction and Management of Plastic Waste in Indonesia

EPR implementation for the reduction and management of plastic waste in Indonesia was first done by PRAISE. PRAISE is a Packaging Recovery Organization (PRO), an association of manufacturers with the aim of promoting and increasing producer commitment to conduct EPR practices in order to convert packaging waste into high-value resources. The association was founded in 2010 by Coca-Cola Indonesia, Indofood Sukses Makmur, Nestlé Indonesia, Tetra Pak Indonesia, Tirta Investama and Unilever Indonesia, producers of food, beverage, home care, and personal care items. PRAISE has three main functions:

- Advocacy
- Research and education
- Partnership and collaboration

PRAISE actively supports and participates in various programs aimed at minimalizing the negative impacts of product packaging on the environment. There are four main pillars that serve as best practices for PRAISE's EPR program:

- Innovation: Implement technology and innovative practices along the product packaging line, including design selection and choice of material.
- Collection: Build and expand network of packaging waste.
- Sorting: Strengthen waste sorting infrastructure.
- Recycling: Support recycling technology to make products with added value.

Achievements by PRAISE members include:

1. Coca-Cola Indonesia.
   (a) PLASTIC REBORN, an educational program on how to recycle and reuse plastic packaging. Through PLASTIC REBORN 1.0, Coca-Cola was able to reach 4300 high school students and facilitate the collection of post-consumption plastic packaging at more than 100 schools and universities in the Jakarta and Bekasi areas. The waste was eventually processed into multipurpose bags with commercial value.
   (b) In 2019, Coca-Cola worked with the Ancora Foundation to launch PLASTIC REBORN 2.0. They cooperated with a start-up company from the waste management field to build a marketplace for waste and recycling, with a

focus on user technology and business acceleration based on post-consumption packaging.

2. Indofood Sukses Makmur.
   Indofood is one of the main producers of foods and beverages. EPR measures for the reduction and management of plastic waste that have been implemented include:
   (a) Product and packaging innovations, such as by reducing the packaging size for sachets, using easily degradable packaging for flour products and applying aseptic filling technology to beverage products to obtain a lighter packaging and reduce waste.
   (b) Management of post-consumer waste by sorting it at its source, and multi-stakeholder collaboration in waste management, such as the Bali Bersih program and the launching of the waste drop box with PRAISE.
   (c) Efforts to recycle packaging waste into resin pellets.
3. Nestlé Indonesia.
   Steps taken by Nestlé Indonesia in the effort to reduce waste, especially plastic waste, include:
   (a) Developing and applying alternative, environmentally friendly product packaging by:
      - Founded the Nestlé Institute for Packaging Sciences for research and development of environmentally friendly packaging.
      - Utilized paper-based packaging for global production of NESQUIK, YES! and SMARTIES brands in 2019 and MILO in 2020.
      - Step-by-step approach to reduce the use of non-environmentally friendly plastic materials for products and/or packaging, and completely halting their use by 2025.
      - Cooperation with multiple parties, such as Danimer Scientific, PureCycle Technologies, and the NaturALL Bottle Alliance, to develop environmentally friendly bottles and packaging.
   (b) Supporting no-waste programs through:
      - Collaboration with the STOP project in Bali and Banyuwangi for the management of marine plastic waste.
      - An integrated community empowerment program in Ngantang, Kebagusan, and Sremsem, covering composting and household waste recycling activities.
   (c) Pushing behavioral change through:
      - Neighborhood cleaning activities by Nestle staff on Ocean Day on 8 June.
      - Waste sorting activities at Nestle's office.
      - Waste sorting activities in the Nestle Healthy Kids Program.
4. Tetra Pak Indonesia
   Tetra Pak produces Tetra Pak cartons made of paper (74%), polyethylene (21%) and aluminum (5%) that can be entirely recycled. The company launched a Used Beverage Carton (UBC) Value Chain System, a system to recycle old cartons from food and beverage products. The program's achievement and targets include:

   (a) Setting collection areas in three provinces—West Java, East Java, and Central Java.
   (b) Working together with five UBC collection partners.
   (c) A 22.5% recycling rate target was reached in 2019.
   (d) In 2020, Tetra Pak targeted even more collection and recycling partners for the UBC and achieved a recycling rate of 24%.
5. Tirta Investama (Danone)
   (a) Innovated Aqua's packaging to become 100% recyclable to reach a recycling rate target of 50% by 2025.
   (b) To support plastic recycling education through a national-scale #BijakBerplastik campaign, which was conducted in 20 large cities in Indonesia in 2020, with a goal to reach five million children and 100 million consumers by 2025.
   (c) Increase plastic waste collection by building infrastructure for collection.
   (d) The creation of Aqualife, the first bottled water in Indonesia made completely out of recycled plastic and can be recycled.
6. Unilever Indonesia
   (a) Unilever Indonesia is committed to ensuring that by 2025, all plastic packaging from Unilever's products can be fully reused and recycled.
   (b) Innovating through the use of CreaSolv® technology that can recycle multilayer plastic waste into new packaging. A CreaSolv® plant was built in East Java with the capacity to recycle three tons of multilayer plastic waste a day. As many as 471 tons of flexible, multilayer plastic waste was recovered from 2016 to 2018.
   (c) Zero waste to landfill system applied at the Unilever headquarters and all factories since 2015.
   (d) Training on sorting waste from its source for Unilever staff, the public, waste banks, waste disposal sites (TPS), and scavengers in East Java.
   (e) Introducing a refill station in packaging-free stores (i.e., Saruga) in Bintaro, South Jakarta, where consumers can refill various Unilever products by bringing their own bottles. Products offered were personal care items, such as Rinso, Molto, Sunlight, Lifebuoy, Clear, Dove, Sunsilk, TRESemmé and Love Beauty and Planet. Unilever charges the refilled products at a 10% discounted rate compared to packaged products.
   (f) Collaboration with Hypermart (retailer) to implement the *Belanja Tanpa Nyampah, Pilah Sampah itu Mudah* program by providing waste collection drop boxes at three Hypermart locations in Surabaya and Sidoarjo. Rewards are given to consumers who submit their waste to a drop box.

Aside from producers included in PRAISE, other companies have also started to implement programs to reduce plastic pollution in Indonesia.

1. The Body Shop
   The Body Shop is a British company that produces cosmetics, personal care items, and perfumes, with stores in various department stores across Indonesia. The Body Shop Indonesia has implemented the Bring Back Our Bottle (BBOB) program, which invites consumers to return empty packaging from The Body Shop back to the company's stores for recycling. This program was first launched in 2008 to reduce plastic waste at final waste disposal sites (TPSA). Since 2014, The Body Shop has worked together with Waste for Change and Eco Bali to recycle empty packaging in Jakarta and Bali. Aside from that, The Body Shop is also active in educating its consumers through upcycling workshops, which have been conducted since 2017. As a result, the number of empty bottles collected experienced an increase each year and the number of bottles collected in 2018 reached 1,454,028 bottles.
2. GO-JEK
   In an effort to implement zero waste to landfill, GO-JEK has worked together with Waste4Change to manage waste from jackets and helmets of GO-JEK riders so that they may be recycled and not contribute to waste generation. With regard to plastic waste reduction and management, GO-JEK has made the following efforts:
   (a) *#NiatMurni Ades*: In October 2019, GO-JEK worked together with the bottle water brand *Ades* to launch the *#NiatMurniAdes* program. Consumers can send old Ades bottles through Go-Send for recycling by Waste4Change as Ades' recycling partner. For every 50 old plastic bottles submitted, consumers will receive 2000 points, equivalent to Rp 20,000, which can be exchanged with electricity tokens, phone credits, or GoPay credits. Ades is a bottled water brand under PT. Coca Cola Amatil Indonesia.
   (b) GOJEK introduced the GoGreener program to its GoFood service by offering users the option to include single-use eating utensils with their orders and providing environmentally friendly delivery bags to drivers to reduce the use of plastic bags. This initiative was done in four areas—Jabodetabek, Bandung, Surabaya, and Denpasar—until December 2019.
3. Starbucks
   (a) In 2018, Starbucks launched the Starbucks Greener Nusantara program. In this program, Starbucks, for the first time, utilized environmentally friendly materials for its products in all of its chains in Bali. This effort to reduce plastic waste is done by providing paper-based straws, plastic bags made out of cassava and eating utensils made out of corn starch. Coffee stirrers made of plastic will be replaced with wooden materials and plastic cups for cold beverages will be replaced with rPET-based cups.
   (b) The Bring Your Own Tumbler (BYOT) is a program where consumers are encouraged to bring their own tumblers when purchasing a drink at Starbucks. On certain days, Starbucks offers discounts to customers who bring their own tumblers as part of its campaign to reduce plastic waste.

4. Nutrifood
   Nutrifood is a producer of nutritional foods and beverages that has been operating since 1979. The company is based in Jakarta. Nutrifood products include Tropicana Slim, NutriSari, Hilo, L-Men, and WRP.
   (a) Aside from implementing the Green Supplier Criteria, Nutrifood has also reduced its use of plastic-based packaging materials, resulting in a decrease in plastic usage by 526 kg.
   (b) Conduct product take-backs and recycling of Nutrifood packaging waste from staff and consumers. Collaboration with waste banks and craftsmen who work with plastic sachets (Nutrifood 2018).
5. P&G (Procter & Gamble) Indonesia
   As one of the largest FMCG producers in the world, P&G is committed to making environmentally friendly products. Some of P&G's responsibilities include:
   (a) Pampers innovated to reduce 30% of the materials for its diapers and pushed forward recycling process for all of its tissues and diaper products. Pampers is committed to launching recycling facilities in three cities by 2021.
   (b) Aim to make all of its products recyclable through innovations in packaging design and choice of material. P&G's target for 2030 is to ensure that 90% of its products can be recycled. As of 2018, as much as 86% of its products can be recycled. An example of one of its measures is:
      - Collaboration with TerraCYcle and SUEZ to produce the first shampoo bottles in the world where 25% of the material is plastic from beaches that have been recycled (P&G 2020).

5.4.2 Challenges of the EPR Implementation for the Reduction of Plastic Waste in Indonesia

Indonesia is still in the start-up phase in its EPR implementation for the reduction and management of plastic waste. As with developing countries that are just starting to implement EPR, Indonesia might face several challenges in different aspects, such as the regulatory, economic, social, and technical aspects of implementation. Below is a list of possible challenges:

1. Limited knowledge and public awareness on waste and environmental management. Public capacity is one of the keys to achieving comprehensive EPR implementation. One small example is the lack of public knowledge and involvement in waste sorting.
2. The lack of infrastructure to support waste management, such as waste collection facilities and transport of sorted waste, makes it difficult for EPR practices to be implemented.
3. The vagueness and overlapping of responsibilities is caused by the abundance of players involved, both in the formal and informal sectors. One example is the complicated bureaucracy at the central government and regional levels, which

have the potential to cause competition with the informal sector or players in the plastic waste chain. As a result, it is very important for producers to collaborate with existing recycling businesses.

4. Weak regulatory enforcement. In Regulation No. P.75/2019, sanctions in the form of negative publicity are still very weak. Transparency might also become an issue as baselines and reports are made by each company. The lack of public information from companies allows companies to set lower baselines or falsely report higher achievements, which may result in free-riding. This issue is compounded with weak monitoring by the government authority.
5. The abundance of industry players, particularly those in the informal sector, makes it difficult for the government to identify responsible producers, which may cause the issue of free-riding among producers. This issue can reduce a producer's willingness to implement EPR.
6. A producer's decision to implement EPR will also influence a product's ability to compete in the market, especially if the producer chooses to charge a fee for the collection and management of waste from consumers, which will affect the product's price.

5.5 Technology and Innovation in Circular Economy (CE) Implementation in Indonesia

Waste issues have become a critical problem of the Indonesian nation's economy, society, and environment. The increased problems of waste production need more circular economy sustainable approaches. Even though waste management is at place, there is limited use of facilities, infrastructure, technologies, and innovations. Currently, the waste management activities are still mostly conducted manually (Aye and Widjaya 2006). However, the circular economy activities including collecting, composting, recycling, gasification, anaerobic digestion, and waste-to-energy systems have not optimally touched the economic, social, and environmental aspects of the waste management system (Fatimah and Biswas 2017). The use of advanced technologies, Information Communication Technology (ICT), and Internet of Things (IoT) that offers effective and efficient approaches to improve waste management in developed countries, very limited adopted in Indonesia current circular economy (Fatimah et al. 2020). The questions are what is the state-of-the-art circular economy technologies and innovation in Indonesia? what are the drivers and challenges? what are the maturity level of the circular economy technologies and innovation? and what appropriate strategies to achieve global sustainability? The study uses literature review, direct observation, interview, and data collected by Fatimah (2020) to answer those research studies.

5.5.1 Circular Economy and Industry 4.0

Industry 4.0 brings rapid technological growth that results in innovations and turns resources into a great number of products at affordable prices. The current "take-make-dispose" activities called linear economy have spread all the world unstoppably. Waste issues have become a critical problem for the global economy, society, and the environment. In 2020, it was found that the world waste reached about 2.01 tons of waste, and it is predicted to achieve 3.40 billion tons by 2050. However, the increasing problems of waste production need a new approach that transforms "take-make-waste" system into a "take-make-return" system called linear economy. A circular economy is an approach that supports the optimization of resources, and the minimization of waste, pollution, and emission. The circularity has been actively adopted by developed countries. Denmark is one of the leading countries that applied circular economy through a significant development of advanced waste management technologies. China has powerful circular economy law and commission. German concerns on energy recovery strategy to transform waste into energy.

Industry 4.0 has also brought new technologies to create more values for circular economy activities. Globally, modern and smart technologies, including ICT, digitalization, and IoT have started to become vena of circular economy business. Adopting these new technologies are believed to improve the economic performance of circular economy industries. Furthermore, this new circular economy system, in 2030, is expected to reduce CO_2 emission by 48%, to save material consumption by 700 million every year in 2030. In Indonesia, the implementation of the circular economy is expected to increase the GDP by 45$ billion in 2020. However, lack of knowledge and skills, limited use of facilities, inadequate infrastructure, and lack of technologies and innovations have burdened the development of the circular economy. It was found that circular economy activity has not optimally touched the economic, social, and environmental aspects (Fatimah and Biswas 2017). The study makes a number of contributions. The study identifies the state-of-the-art current circular economy technologies and innovations applied in Indonesia, the barriers and driver for the development of circular economy technologies and innovations, the level of maturity of circular economy technologies and innovations used by some cities in Indonesia, and the strategies involving stakeholders' participation.

5.5.2 State-of-the-art Circular Economy(CE) Technology and Innovation

Technology development and innovation are the main engines of current and future circular economy development. Technology and innovation in the circular economy fields initiate the development of better services and products produced by the system and improve the internal process. Technology provides better efficiency and effectiveness of circular economy approaches. Innovation offers new methods, tools, and approaches that could improve the circular economy system. Innovation is also part of business strategies to transform the idea into real value products or services.

5.5.2.1 Global Perspective

Current circular economy especially for world waste management and treatment technology from collection to disposal process has rapidly improved with more efficiency and greater environmentally sound practices.

For the collection process, the advanced methods of waste collection including Geographic information system (GIS), monitoring solid waste system/bins, and indoor/outdoor waste compactors have been started being adopted by some countries (Yoshida and Yoshida 2012; Wajeeha et al. 2016). In addition, GIS technology is used to manage each phase of the waste entire cycle of waste production sources to the final treatment or disposal center (landfill). The other technology called Global System of Mobile (GSM) (Hannan et al. 2010) uses sensors on public garbage bins to identify the level of waste inside of the bin (Misra et al. 2018). Instead of the development of advanced technologies, new platforms for smart waste collection and sorting have been also developed. Smart Bins are trash bins equipped with ultrasonic sensors to measure the space of the trash that has been developed. In this platform, a sensor gateway uses the WLAN protocol, while the cloud platform is used to collect, analyze, and visualize the junk data use (Zanella et al. 2014).

For waste processing, the latest waste management technologies are known as autoclaving, fluffing, and melting technology (Gao and Li 2011). Autoclaving technology applies steam treatment which is used to sterilize the waste and to screen the residue. On the basis of weight, while glass and dirt are separated and removed from organic fibers, that fiber is used for land applications and Refuse-Derived Fuel (RDF) production and the metals and plastics are sent to the recycling process (Sarc and Lorber 2013). Fluffing is a separation and sterilization technology for solid waste, in which the organic waste is transformed into pulp material (i.e., fluff), that is rich with organic base and high nitrogen. The next technology is melting technology, which has a function to melt the waste to reduce the waste volume by fuel and electricity combustion. This technology solves the fly ash problem and stabilizes metal portions, which is better than incineration. Vermicomposting is waste technology for managing animal, pharmaceutical, food, and sewage wastes, and transforming them into vermin wash which consists of high nitrogen, phosphate, and potassium contents.

Energy recovery technology in which all waste residues are inaugurated for a renewable energy alternative is the last technology before the disposal process. This technology consists of bio and thermal conversion technologies that convert organic and inorganic waste (plastics, computers, tires) into useful chemicals through processing system thermal. Following the technologies are advanced thermal treatment technologies, such as pyrolysis, gasification, and biofuel. Pyrolysis converts waste to liquid or gaseous fuels together with the residue, while Gasification is partial oxidation of a substance, which occurs between combustion and pyrolysis, and Biofuel is fuels produced from food waste through fermentation processes.

(Ministry of the Environment 2012; Srivastava 2016; Wajeeha et al. 2016; Millard 2017; Tisserant et al. 2017; Artiola 2019).

The final stage is the waste disposal process, in which residue of trash, recycling, and other waste treatment technology are discarded. The landfill is believed an efficiently engineered depression for final disposal in low-population areas. The bioreactor is the other latest technology to process waste disposed of, that has the objective to improve the decomposition rate, leachate circulation, and microbial growth. The latest technology that is commonly applied to small-scale projects to generate electricity from waste is used microturbines (Pariatamby and Tanaka 2015; Bronson 2017).

5.5.2.2 Indonesian Perspective

Waste management especially in a big city is still a big problem in Indonesia, from the source of waste (segregation and collection system) to the end pipe of waste (treatment and landfill systems). The waste segregation activity of Indonesian people is still very low which is about 18.84% of total waste. However, the initiative of dropping boxes program is expected to increase the amount of waste collected from the people. Compactors facilities for waste transportation process are only available in some big cities. The waste transportation and collection processes are handled by the local government and private sectors. Individual sectors such as scavengers, waste banks, and private waste collection enterprises have an important part in this transportation process. Waste processes including composting, gasification, recycling, refurbishing, and remanufacturing are commonly found as economic support for community and small industries. These activities are a potential business for Indonesia's future small and medium industry. Even though the majority of the process have limited technology and automation process, this process is human-intensive activities that are good for the local community economy. In the last waste management process, open dumping waste management is the common landfill system. Few of them are controlled and are sanitary landfills, while many of them are managed as a waste mountain. Waste to energy technologies have been applied by the Indonesian Government as a priority program to reduce waste and to create value for the waste. However, the program that is projected to be applied in 12 cities of Indonesia (e.g., Surabaya, Makasar, Bandung, etc.) has not been successfully completed and implemented due to an uncoordinated regulatory system.

The current 4.0 industrial revolution has also generated the application of information communication technology in the Indonesian Circular Economy business. Some web and android-based applications for waste collection system (e.g., smash) have been introduced to the Indonesian community to reduce the waste and to monetize the waste.

5.5.2.3 Drivers and Challenges for CE Technology and Innovations

The current 4.0 industrial revolution through digitalization and artificial intelligence offers the achievement of sustainable and advanced technologies in one direction. The potential opportunity of the high and digital technology applications (e.g., sensors, cloud) in a circular economy business is widely open.

Digitalization is distorting the physical, biological, and digital fields, that use physical and software components starting from the waste collection, processing, treatment, and disposal stages. Digitalization is characterized by physical and computational elements, complex and high automation, sensors, actuators, and human-system interaction that are required in the current waste management system activities (Kokila et al. 2017; Neligan 2018). The ultrasonic waste bin uses sensors to identify the capacity and performance (i.e., waste bin level) of the bin at all times. The next innovation is digital route optimization to help optimize the mobility of waste collection and transportation by applying the Global Position System (GPS). The sensor is mostly implemented in the waste sorting process to recognize the various waste characteristic and materials. While wireless technology (e.g., RFID) is commonly used to monitor the waste transportation process. Furthermore, Cloud and CPS have been adopted into some treatment processes (e.g., recycling, remanufacturing) to support the waste recovery process (Gu et al. 2017; Kaushik and Yadav 2017; Adam et al. 2018; Aleyadeh and Taha 2018).

The drivers for developing this advanced technology in circular economy activities are the technological, regulatory, and market demands, effective and efficient process, and product affordability, long life, and quality. The industrial revolution, globalization, and dynamic market demands have created a high demand for smart technologies and products. The green label has stuck on the industry brand if they want to be competitive in the global market. Standardization is referred to high-quality products that become the main priority of customer requirements. These all product's requirements can be met with the automation and Information Communication Technology adoptions. The global commitment to producing green products, eco-label products, and sustainable products has spread all around the world as new competitive issues to be met by worldwide industry. Ontime, effective and efficient process and delivery in circular economy supply chain have also become industry orientation priority. Reverse logistic infrastructure is urgently required to meet the marketplace of the circular economy.

On the other side, the challenges for developing this advanced technology in the circular economy include the regulatory barriers, the lack of stakeholders' behaviors and attitudes, the limitation of technology investments and funding, inappropriate supporting infrastructures and facilities, and limited knowledge and skill for advanced technologies. The regulatory barriers include a lack of global consensus of the circular economy, low regulatory enforcement, and the target achievements. In addition, limited incentives given to circular economy stakeholders (i.e., industry) that applied green and efficient technologies and energy have also become barriers to develop modern and smart technology. Stakeholder behaviors and attitudes are one of the big challenges for developing a sustainable and smart circular economy. Many are still believed that the wastes of their activities are not their responsibility. Wastes management, clean environment, and healthy environment, especially in the public area are government tasks. However, leadership from Government authorities is seen to be one of the key drivers of technology development in the circular economy. However, lack of government leadership has burdened the circular economy development. Financial barriers are the other burden faced by many industries. Financial barriers are usually more concerned with the market. High expectations of the customer to high and affordable products create the same expectation to waste-created products. Poor business cases are sometimes referred to low quality thus creating low income and benefits by the enterprises. The business leads to poor performance, thus very difficult to get external investment funding for technological dan innovation development. Lack of government investments has also become one of the potential problems.

5.5.3 Circular Economy Technology Adoptions

Circular economy technology adopts in Indonesia is usually driven by the situation in different cities—not vice versa. The adoption of technologies is justified by the situation in the cities that offer a new system to meet the city's requirements. This study concerns waste management technology as the priority to be discussed and analyzed. The improvement to develop cities waste management system have been found to be related to the development of the city. To identify the use of technologies and innovation in Indonesia's circular economy, some technological dimensions of sustainable waste management presented in Table 5.1 are used in this study.

Table 5.2 presents the maturity stages of waste management technologies that are divided into traditional, common, organized, integrated, and smart (Fatimah et al. 2020). The Linkert scale is used to measure the scores of each criterion. This maturity level is categorized into global criteria and technology and innovation criteria. The level of maturity comes from low to high and is structured into traditional, common, organized, integrated, and smart. The score in Table 5.2 shows the lowest and highest range.

Table 5.1 Technological dimensions of sustainable waste management

No	Features—subdimension	Infrastructure, facilities
1	Availability of appropriate technologies to transform waste into valuable materials/energy	Treatment technologies, recycling, waste to energy, remanufacturing, composting, etc., gasification, incineration
2	Availability of digitalization application, ICT, and IoT innovations	Sensors, GPS, mobile application, cloud system, artificial intelligence, cloud-based waste data
3	Availability of automatic technology from collection to treatment process	Automatic system, robotic, automatic conveyors, cranes, excavators
4	Availability of smart transportation vehicles and infrastructures	Number of transportation vehicles (i.e., Trucks), that are interconnected and facilitated with ICT
5	Availability of efficient energy consumption technology	Number of sustainable, green or renewable technologies (energy-efficient technologies)

Table 5.2 Maturity level of technological waste management

Level	Scores	Global criteria	Technology and innovation criteria
Smart	86–102	(a) Workers are highly skilled	(a) Automatic technology and systems are employed to achieve efficiency
	14–15	(b) Community is naturally involved in the system	(b) Waste management system is globally connected through the entire system
		(c) Insurance and other initiatives are available for health, hygiene, and safety occupations	(c) Robotic activities, waste data, and information are integrated into big data centers using IoT systems and artificial intelligence
		(d) The system's compliance style is founded on self-regulation	(d) All information is available real-time, and all personnel are committed to a culture of environmental awareness
		(e) Waste treatment values are considered in the decision-making in the system	
Integrated	73–85	(a) Modern and aligned with the behavior of the people	(a) Waste management system is comprehensively and intensively integrated to reduce waste using IoT
	12–13	(b) Standard skilled workers operate beyond regulatory compliance	(b) Collaboration with the recycling industries and other stakeholders to achieve supply chain
		(c) All management levels involved in a culture that values environmental awareness	(c) High level of communication and transparency
Organized	58–72	(a) Efficient, streamlined, effective waste management process	(a) Promoting worker productivity through automation and improved monitoring
	10–11	(b) Established communication channels between department	(b) ICT investments, a website/portal to disseminate and to promote waste management activities and to share pertinent information
Common	43–57	(a) Communication between departments to handle the waste	(a) Waste management is addressed to meet the waste regulations with a primary focus on accessibility to the collection process
	8–9	(b) Lack of coordination between stakeholders.	(b) Semi-automatically operated ICT applications are used for basic communication, and regulations drive the waste management process
		(c) Regulations drive the waste management process	
		(d) A minimum number of skilled workers are employed	
Traditional	30–42	(a) Regulations are applied at the very basic standard to meet government requirements	(a) ICT investment is limited to the use of information alerts for waste data confirmation

(continued)

Table 5.2 (continued)

Level	Scores	Global criteria	Technology and innovation criteria
	5–7	(b) Little participation from the community and citizens	(b) Limited facilities and technology with minimum machinery
		(c) Lack of communication between municipal departments	(c) Automation mostly manually operated
		(d) Lack of skilled workers and lack of regulation compliance	(d) No standard process and procedure no communication channels

Source: Author Data Processing Results

5.5.4 Case Studies

Case studies applied in four main cities in Indonesia including Jakarta, Magelang, Semarang, and Surabaya have shown different adoption of circular economy technologies and innovations, and different performance levels. The regulations and policy to follow waste management and the availability of interaction link between community, government, and the industry is well organized. However, a lack of performance is found in the adoption of technology and ICT for collecting, sharing, and receiving waste data, community participation, government funding, and transparency and accountable investments for waste management.

To identify the current adoption of waste management technologies and innovations in the four cities, an assessment has been done and presented in Table 5.3.

Table 5.4 presents an assessment of the technology maturity level of the four cities, which is presented as common, variety, and diverse maturity levels. The common technique is known, easily available, and commonly used, while variety means the technology has different types, categories of collection, transportation and treatment technologies, and diverse is the highest level of sustainability that shows the best variety of different, specific, and unique.

Table 5.3 Current performance of waste management technologies and innovation

No	Cities	Current waste management technologies and innovations
1	Jakarta	The major circular economy technologies and innovation used in the municipal waste and waste treatment industry include conventional transportation, integrated final disposal Centre (i.e., Bantar Gebang), Centre for the intermediate treatment facilities (e.g., Sunter). Wastewater management installation (IPAS) that handle about 470 m^3 water waste/day. Recycling, remanufacturing, and reconditioning are commonly practiced. Landfill gas management that produces electricity about 3 MW, composting and greening in TPST, count block, and asphalt materials productions, waste to energy to produce about 700 kw/h electricity with a waste capacity about 100 tons/day, and three-recycle application for waste trade management (trash for cast), online waste management system (SMASH), etc.
2	Surabaya	The circular economy approach for major waste collection process is still using a conventional system in which the waste is collected using dumb truck transportation (local government collaborates with the private companies). The waste treatment technology uses integrated waste management. Waste to energy at Benowo with a total capacity 11 MW is expected to produce electricity for the city. The other treatment technology is project waste management installation acceleration (technology based). In this place, about 1300–1500 waste is produced waste to energy. The local government uses the technology of gasification power plant by collaboration with China. JALISOB—Waste bank online transaction for waste buying and recycling
3	Semarang	Integrated waste treatment facility (TPS3R and TPST) is applied in this city, with one landfill called Jatibarang, which serve all Semarang areas. Waste collection is done by using different types of bins using mainly conventional transportation vehicles (dump trucks). Treatment technologies consisting of the sanitary landfill (using controlled landfill methods), composting, recycling, and methane gas technology are used for the community. Waste to energy is at the early stage to be developed. Silampah is one application created to facilitate waste accumulation report for local government to make the waste management decision making. Waste Transportation use dump truck (Maryono and Hasmantika 2019)
4	Magelang	3R (reduce, reuse, and recycling) approach is a common waste management system applied in this city to reduce the amount of landfill waste. The organic village which offers waste reduction, reuse, recycling, and saving, is an important part of waste management in this city. The waste final operational system of landfills is open dumping, and waste technologies are limited. Waste management called online waste bank application is one of the online applications for community to monetize organic and non-organic waste in this city

Source: Author Data Processing Results

Table 5.4 Waste management technology maturity level of case study

Sub dimension	Threshold	Jakarta	Surabaya	Semarang	Magelang
1. Integrated treatment technologies, recycling, waste to energy, remanufacturing, composting, gasification, incineration	3	2	1	1	1
2. Sensors, GPS, mobile application, cloud system, artificial intelligence, cloud-based waste management data	3	2	2	1	1
3. Automatic systems, robotic, automatic conveyors, cranes, excavators for waste management	3	2	2	1	1
4. Number of waste transportation vehicles that are interconnected	3	1	1	1	1
5. Number of sustainable, green, or renewable technologies (energy-efficient technologies)	3	2	2	1	1
Total score	15	9	8	6	6

Source: Author Data Processing Results

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Part III

Implementation Status of Circular Economy Concepts

6 On the Way to Circular Economy: Türkiye's Waste Management and Zero Waste Project

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Abstract

Türkiye is a bridge and the crossroad between the Middle East and Asia and Europe. The economical and social growth gets Türkiye as a good sample and center of attraction for the neighboring developing countries. Türkiye is a comprehensive model for many developing countries with the developments in the waste management area as in the other fields. One of the most important steps taken in waste management is the "Zero Waste Project", which has been implemented throughout the country. Zero Waste Project was launched in collaboration with the Ministry of Environment, Urbanization, and Climate Change in 2017. Through the project, within the framework of sustainable development principles, zero waste applications have started. This chapter evaluates waste management with the existing data from the Ministry of Environment, Urbanization, and Climate Change and provides an overview of the development of waste management practices in Türkiye. The current situation regarding the amount of municipal waste and waste management system is explained. In addition, information about recovery and recycling practices in the country is given. Finally, the zero waste project was introduced within the scope of sustainability practices. Finally, within the scope of sustainability practices, the zero waste project was introduced and the planning in the field of waste management within the framework of circular economy was mentioned.

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Keywords

Türkiye · Waste management · Circular economy · Waste Management Legislations · Zero Waste Project

6.1 Introduction

It is predicted that the world population, which is 7.7 billion by 2019, will reach 9.7 billion by 2050 (Department of Economic and Social Affairs, Population Division 2019) and the amount of waste produced will be doubled (OECD 2020). The annual waste generation is estimated to be 2.1 billion tons and it is reported that approximately 13.5% of this waste is recycled and 5.5% is converted into compost (Adekola et al. 2021). Türkiye's population, which is around 82 million including refugees received in the last years, is expected to reach about 93 million by 2050 (Belen et al. 2019). In parallel to the world's waste management metrics, about 90% of urban waste is sent to landfill in Türkiye. The proportional percentages of the components in the waste have also changed considerably and will continue to change with population increase. An example could be the electronic wastes (WEEE). Although WEEE were not a big concern from the point of waste generation rates in the past, today WEEE become one of the fastest growing waste streams, as they are a source of secondary raw materials. Additionally, ash from fossil fuels was an important waste component in the past, today there is a significant decrease in ash generation especially for developed countries.

After the industrial revolution, the demand for natural resources has increased rapidly. As a consequence, raw material resources started to decline, and therefore, increasing needs brought the researchers to seek for alternative raw materials and energy sources. The foundation of circular economy is based on a holistic approach to resource efficiency. Apart from the use of renewable energy sources, smart agricultural practices, effective waste management strategies, clean industrial processes and products construct the main components of the circular economy. However, in order to meet the food needs of the increasing population and to obtain more products from the field, agricultural lands were subject to some risks such as unconscious and inappropriate pesticide and fertilizer practices, which disrupted the natural structure and characteristics of the soil, which in turn jeopardize the quality of water resources. In order to reduce the pressure on the resources and detrimental environmental impacts, it is necessary to take measures on renewable energy resources expansion, sustainable agriculture practice dissemination, waste generation minimization, and raw material reuse increase.

As known, sustainability is a multi-dimensional and multi-stakeholder concept. From the point of sustainable waste management, the need to evaluate and redefine waste with a holistic approach has emerged. The search for increasing the quality of life by reducing resource consumption and waste production has revealed the circular economy model (Bonciu 2014). In order to achieve sustainable development goals, the transition to a circular economy is important (Önder 2018). New regulations are also introduced to contribute to the circular economy with renewed waste management plans (Brears 2018; OECD 2019a; Koçan et al. 2019). Even though the environmental and economic impacts of uncontrolled consumption of resources would seem to be on a regional scale at the moment, the consequences will be global in the long term. This situation brings a responsibility to decision-makers to take appropriate measures. In the recent years, there has been an increasing trend regarding the effective use of resources. In this line, agreements among many countries on a global scale have been signed, targets have been set and measures have been brought to the agenda. With increasing awareness and new economy model, the concepts of "secondary raw material", "smart city", "sustainable structures", industrial symbiosis, "remanufacturing", "repair", "ecodesign", "cleaner production", "minimalist life", and their applications began to spread. For a sustainable circular economy, appropriate management of limited resources, that is, waste reduction, carbon footprint mitigation by switching to carbon neutral practices, and water footprint reduction are necessary.

Waste is not only generated as a result of the use of the product, but also during the supply of raw materials, production, delivery to the user, and subsequent disposal. In the linear economy, the products consumed turn into waste without entering the economic cycle (Eskin 2020). As in the definition "The circular economy is where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized." by the European Commission (EC) (2015), "waste" is considered as a resource in almost all definitions of the circular economy (OECD 2020) and waste management plays a key role (EC 2015). In other words, the circular economy is the economy model with the lowest amount of waste (Önder 2018). With the implementation of the circular economy model, new business areas, employment, and markets will be provided, and technology development that will ensure long-term product use will be encouraged. Thus, environmental impacts will be reduced and the pressure on resources will decrease together with greenhouse gas emissions.

Although the definition of circular economy has been introduced by the European Union (EU) (Koçan et al. 2019), steps have been taken in some countries regarding the circular economy model that will increase their own resources and reduce environmental impacts. Being a member of EU, Germany is among the countries that successfully implemented this model with the circular economy law enacted in 2012 (Özsoy 2018). Germany achieves the targets set for 2030 in the circular economy model by sending 65% of its waste to recycling and 5% to regular storage (Özsoy 2018). France, on the other hand, started the necessary arrangements for this process under the roof of the Circular Economy Institute, which was established in 2013 (Bonciu 2014). As of 2015, the amount of waste sent to regular landfills in Switzerland, Sweden, Denmark, the Netherlands, Norway, and Austria is lower than 6% (Ghosh and Agamuthu 2018). In Denmark, a number of legal regulations have been implemented in addition to practices such as packaging tax, deposit, and building energy label (Brears 2018). In addition, "The Fund for Green Business Development" supports green industrial symbiosis for resource efficiency (Brears 2018). It is stated in the OECD report that Japan, South Korea, and the Netherlands are well ahead in terms of their circular economy policies implementation (OECD 2019a). Japan supports many investments that implement 3R. For example, ecological city practices including urban planning and recycling are supported in the “Eco-town” program (OECD 2019a). South Korea updated the legislation on waste management in line with the circular economy under the “Framework Act on Resource Circulation” and stated that the amount of waste to be recycled will be 87%, and the amount of waste to be sent to the landfill as 3% (OECD 2019a). It is thought that factors such as the need for resources and the need for space for waste disposal accelerated the transition to circular economy in these countries. In Türkiye, although environmental issues are taken into consideration in the development plans after 1973 concrete steps have been taken through the harmonization process with the EU (Eskin 2020). It is known that significant progress has been made especially after 2008 (OECD 2019b). Studies on the subject have accelerated in the recent years, and an important step was taken in transition to circular economy with the Zero Waste project which was initiated in 2017 (Eskin 2020).

In this chapter, the principles and mechanism of circular economy are given, and the assessment of waste and circular economy interaction, the transition from a linear economy to circular economy processes, methods, and technologies with practical examples and legislative arrangements are presented. In addition to these, measures and suggestions that can be taken for the future are also included.

6.2 The Circular Economy

The concept of sustainability varies depending on the system and concept in which it is used. In a system, where economic development is taken as a reference, Marull et al. (2013) define sustainability as “improves the well-being of people, reduces energy consumption and preserves quality of the ecosystems”, while Gerdessen and Pascucci (2013) defined it as “achieves the best social, economic and environmental consequences” (Salas-Zapata and Ortiz-Muñoz 2019). The United Nations (UN) Brundtland Commission defined sustainability in 1980 as meeting the needs of today’s society by taking into account the needs of future generations (Scott 2015). Based on these definitions, one can say that it is not possible to ensure sustainability with the current economic system. In the linear economy model that has been in use for a long time, the negative effects of the take-make-dispose applications have started to be seen on a regional and global scale. Therefore, it is inevitable to shift to a new economic model as the resource consumption is faster than the renewal of the resources.

The Green Economy model (Lavrinenko et al. 2019), which advocates the approach that economic development can be achieved by reducing environmental impacts, and The Blue Economy model (Wenhai et al. 2019) where sustainable use of oceans and seas is ensured, and The Circular Economy models that address sustainable development goals more comprehensively (Önder 2018) have emerged as much better alternatives than the current system. It is clear that the economic model, which aims at economic development by minimizing the negative effects on natural resources and the environment, is the circular economy model which considers the needs of future generations. The advantages, development process, principles, and foundations of the circular economy model over the linear economy model will be evaluated in the following sections.

6.2.1 Linear Economy vs. Circular Economy

The linear economy applied in more than 90% of the world economy (Akpulat 2020a) is a system that consists of production, consumption, and disposal processes of a product. In this economy model, waste is evaluated as an unwanted output that needs to be disposed of, resources are used intensively and the main focus is on economic gain. In this model, waste not only occurs during the consumption phase but also during the production phase (Önder 2018). Here, the raw materials extracted from the source form the basis of the production process. However, the approach in the circular economy is just the opposite. Today, it is necessary to raise the awareness that waste is essentially a valuable resource and that it can be recycled again and again.

Production—transportation—consumption and disposal processes in the linear economy model have negative effects on the environment, especially from the point of climate change, consumption of resources, and the formation of large amounts of waste. Waste generation occurs at every stage of raw material extraction, production, and utilization processes (Eskin 2020). While products are produced from scratch in the linear economy, in the circular economy, the use of resources is less as the resources are used over and over again through recycling. In addition, in the circular economy model, less environmental footprint and sustainable resource management stand out instead of more products and earnings. If this new model will be adopted, the current consumption habits will have to change. In this system, in which the cycle in nature is taken as reference (EC 2015), it is essential to ensure that the products stay in the cycle for longer periods of time and a product that has completed its useful life should be evaluated (Figs. 6.1 and 6.2).

In case that the linear economy model is continued, besides the effects of climate change, environmental pollution, consumption of resources, the decrease in water resources, decrease in agricultural areas, biodiversity, inability to meet food demand, inadequacy of public services such as health, school, transportation, and unemployment will also emerge on a social level (Fletcher 2019). In the linear economy, the resources are under the risk of depletion, the environmental pollution would be a serious problem, and apart from these the economic development would be negatively affected. In the circular economy, however using wastes as secondary raw materials saves resources and eliminates the need and costs of disposal. Compared to the unsustainable linear economy which focuses on economic gain, in the circular economy, resource efficiency, environmental effects, and related costs are evaluated together and the needs of future generations are also considered (Eskin 2020). Evaluating the negative consequences of the linear economy application such as climate change and rapid depletion of resources, it is clear that the new economic

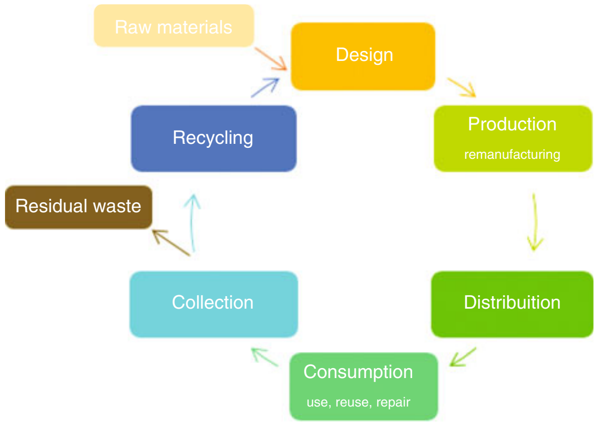

Fig. 6.1 The balance between society, environment, and economy, which forms the basis of the UN's Sustainable Development Goals, is very important in terms of sustainability and takes into account the needs of the next generation as well as the needs of today's people (Fletcher 2019). In other words, linear economy represents an unsustainable system, whereas circular economy represents sustainability. The main differences between the linear economy and the circular economy are given in Table 6.1. As can be seen from Table 6.1, the circular economy model is a model for meeting the needs of today and the future

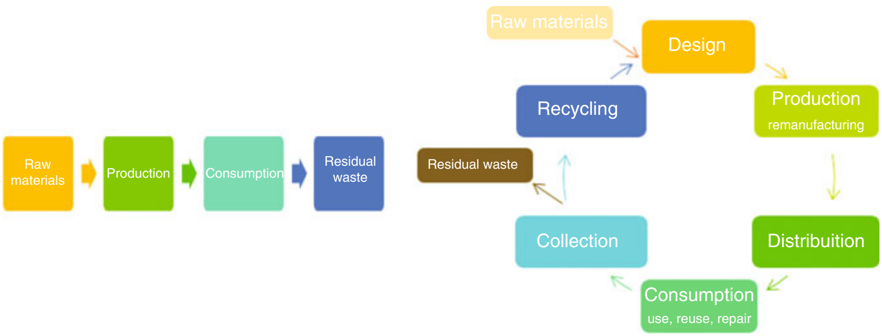

Fig. 6.2 A schematic flowsheet for linear (left) and circular economy (right). (Modified from Akcil 2016)

model will have to be adopted worldwide. In order to realize this transformation effectively, its basic principles and functioning mechanism should be understood and applied accordingly by the decision-makers and related governmental organizations.

Table 6.1 Linear economy vs. circular economy

Linear economy	Circular economy
High sales, profit and industry oriented	Environment and resource oriented
Negative environmental impact	Environmental protection
Everything is built from scratch, primary raw material use	Can be evaluated as secondary raw material
The product turns into waste	Waste generation is minimized
Quick consumption of resources	Protection of resources
The main focus is today	Main focus is future generations
	Reducing foreign dependency
	New jobs and employment opportunities
	Contribution to the economy

6.2.2 Background and Development of the Circular Economy

With increasing pollution of soil, air, and water with anthropogenic activities, the depletion of resources, and the emergence of other adverse effects, a search for a new perspective was initiated. Since the current economic system can no longer support the current waste management system, it is very important to switch to the circular economy model (Romero-Hernández and Romero 2018). The concept of zero waste, based on the reuse of products, was first introduced by Paul Palmer in the 1970s (Zaman 2015). The concept of circular economy was first used by Pearce and Turner in 1990 (Qi et al.2016), and the first application involving recycling and waste management in the circular economy was applied in Germany in 1996 (Erat and Telli 2020). Due to the negative effects of the linear economy model mentioned earlier, waste prevention has been one of the primary goals in the circular economy model. The 3R hierarchy aiming better management of waste is not enough to take advantage of the potential value of the waste. For the transition to a circular economy, a restructure-improvement is needed, in which the potential of waste is much better evaluated (Romero-Hernández and Romero 2018). In waste management applications, there is a transition from 3R to 5R, and even to 9R, which includes sustainable waste management and zero waste processes. In waste management, the wastes generated in the 3R model, which was previously preferred, are reduced, reused, or recycled with some measures before disposal. Among the 3R, recycling should be considered as the last choice before disposal in waste management hierarchy as it will involve the production and processing processes (Tran 2019). The 5R application emerged with the concept of Zero Waste. The aim here is to keep the product in the cycle for a long time and to reduce the amount of waste that needs to be disposed of as much as possible. The first priority in the 5R model is not to generate waste. If it is to be generated, as a second option the generation should be minimized. This is followed by repair and maintenance of the product after its first usage purpose or re-evaluation for a different purpose. Finally, as a last choice recycling alternative is recommended, in case other R alternatives are not

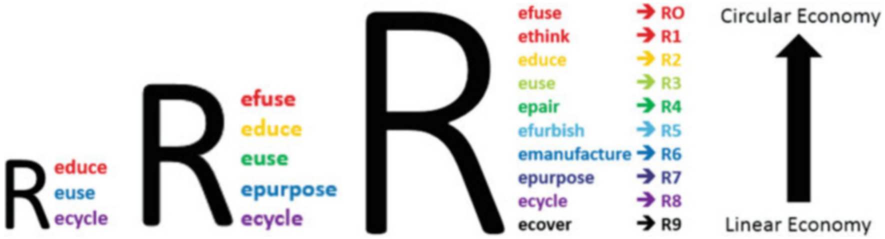

Fig. 6.3 3R, 5R, and 9R waste management models. (Adapted from Potting et al. 2017)

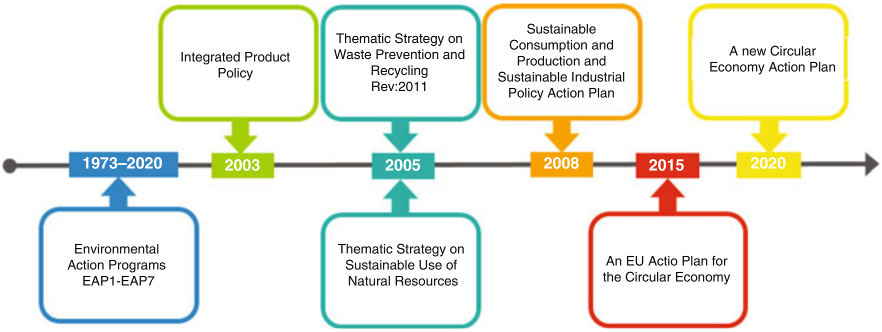

Fig. 6.4 Toward circular economy (EU). (Adapted from Akpulat 2020b)

applicable (https://www.circlewaste.co.uk/2020/09/16/what-are-the-5-rs-of-waste-management/). Although the 3R framework is the first and the most common application at the moment for most of the countries, 9R draws a more comprehensive and more compatible framework with the circular economy model (Okorie et al. 2018). The 9R model consists of ten stages. As we move from R9 to R0, the circularity increases from the beneficial use of materials to the use and manufacture of smarter products. If the last alternative in waste management hierarchy is not considered as waste recycle (R8), the alternative of obtaining energy from the product/waste with the recovery (R9) step should be considered (Okorie et al. 2018; Özsoy 2018) (Fig. 6.3).

The development process of the circular economy takes place in different stages such as recycling of waste, gradual reduction of waste emissions, zero waste approach, and inclusion of the society in this process with production and consumption habits (Wu 2014). In fact, the concepts of sustainability, protection of resources, climate change, and protection of the environment interact with the circular economy process in relation to each other. Some steps have been taken in these contexts during the transition to a circular economy. Significant progress has been made with various plans and agreements in relation to the circular economy process such as sustainability, environmental protection, waste management, and climate change both in Europe (Fig. 6.4) and worldwide (Fig. 6.5).

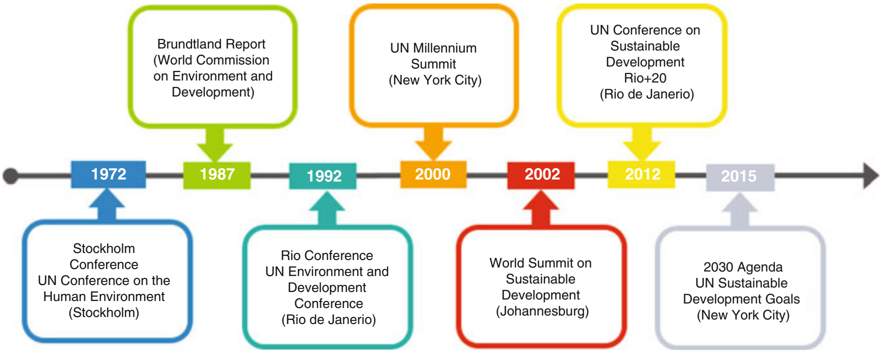

Fig. 6.5 Toward circular economy. (Adapted from http://www.mfa.gov.tr/surdurulebilir-kalkinma.tr.mfa)

The issue of environmental protection started to be on the agenda in the 1970s (first Environment Action Plan, Stockholm Conference). The concept of sustainable development was first defined in the Brundtland Report in 1987 (http://www.mfa.gov.tr/surdurulbilir-kalkinma.tr.mfa). With the Kyoto protocol adopted at the third Conference of the Parties in 1997, it was aimed to reduce carbon emissions. Green Economy was initiated under the leadership of UNEP in 2008, and then the maximum utilization of oceans and seas came to the agenda at the Rio+20 Conference in 2012. The Paris agreement was adopted at the 21st Conference of the Parties, in which measures to reduce the impact of global warming were brought to the agenda in 2015 (Clark 2020; Eskin 2020). Sustainable development goals have been determined in the development program of the UN. The circular economy is also supported by the Paris Agreement in 2015 and the sustainable development goals in the UN 2030 agenda (Eisenriegler 2020). At the same time, the transition to the circular economy contributes to sustainable development goals such as Goal 8 "Decent Work and Economic Growth ", Goal 12 "Responsible Production and Consumption", and Goal 13 "Climate Action". In the same year, the Circular Economy Action Plan of the EU was introduced (EC 2015). In March 2020, the New Circular Economy Action Plan for a cleaner and more competitive Europe was announced, including climate change and reduction of greenhouse gas emissions (EC 2020). These stages in the transition to circular economy form the basis for the maturation of the process.

6.2.3 Principles and Mechanism of Circular Economy

The transition to a circular economy is possible by reducing waste generation and negative environmental effects as much as possible while reusing resources. The basic concepts of the circular economy are the components in the 9R hierarchies mentioned in the previous section. In order to have a valid circular economy model, the R requirements must be applied at all stages of the cycle from the design process to the consumption process (Fletcher 2019). It should be noted that the primary goal, here, is not to generate waste. Thus, the amount of waste to be sent to landfill will be minimized. In the circular economy action plan of EC, it is aimed to reduce the amount of waste that will go to landfill to below 10%. Apart from these, effective and efficient use of resources and renewal of natural systems, prolonged product life cycles, and ensuring sustainability in production and consumption form the foundations of circular economy (Fletcher 2019; Güngör 2019; EC 2020). It is predicted that there will be a significant decrease in greenhouse gas emissions if the circular economy model can be applied. Since energy, other industrial production processes and waste disposal processes are important emission sources, they can be considered as targeted areas of the circular economy model, so a significant reduction in emissions from these processes is expected.

Since the production of a product is directly related to the consumption of raw material resources, the priority in product design is to choose the products that can be used for a long time. This requires the product to be durable, repairable, renewable, updated, or reproducible (EC 2015). Since the production need will decrease with the long-term use of the product, the consumption of limited resources and the reduction of waste generation will mitigate environmental impacts, especially greenhouse gas emissions. In addition, new business opportunities will be created by optimizing resource utilization. Therefore, it would be possible to develop new manufacturing industries in which the secondary raw materials available in the economy are kept in the loop. The EC (2015) recommends the sharing of waste or by-products in industrial processes and industrial symbiosis. The waste or by-product created in this way will be evaluated as a raw material in another sector and will contribute to the economy in many ways. However, the quality of the secondary raw material is an important parameter to consider.

In the circular economy waste management hierarchy, reuse and recycling options are alternatives that should be considered before disposing of waste, so that the amount of waste sent to landfill is expected to be reduced as much as possible. The wastes that cannot be recycled or reused is preferred to dispose by means of landfill or incineration options where environmental impact is reduced, and if possible, energy is obtained.

In the transition to the circular economy model, it is necessary to make innovations and changes in the production process of the products with less environmental effects on a sectoral scale (with applications such as new technologies, eco-design, industrial symbiosis), while the consumption habits need to be changed with increasing awareness of individuals and organizations. It is evident that consumption habits of individuals as well as organizations will affect the circular economy. Individuals' preferences for energy-efficient, affordable, repairable, and durable products affect their production processes. The dissemination of this transformation process, supported by incentives and trainings, will manifest itself with improvements in both resource management and environmental indicators (EC 2015). In this model, since the renewal-repair-waste management processes will be carried out by the manufacturer company, it will not be the responsibility of the user (Güngör 2019). Especially for some electronic products, proposals such as right to repair and product-as-a-service leasing systems have been proposed (Akpulat 2020a). With this business model, developing renewable products with a longer life will become widespread. Thus, the producer firms will be able to evaluate their own resources, while the producer and the user will gain profit, while also contributing to the circular economy.

The priority areas determined by the EU commission for the circular economy process to ensure sustainable development goals are as follows (EC 2015):

- Plastics (recyclability, biodegradability)
- Food (taking measures to reduce waste generation)
- Critical raw materials (components that are mostly found in electronic devices, with high economic value and in which the negative environmental impacts of the extraction/processing process may be significant)
- Construction and demolition wastes (recyclability of the wastes generated, development of environmental performance indicators of buildings)
- Biomass and biobased products (the use of these biodegradable products is supported and at the same time, it can contribute to the circular economy by using it in the production of biofuel, a renewable energy source).

It is expected that both environmental and economic benefits will be achieved with investments and regulations in these priority areas.

The main challenges in the transition to a circular economy are listed as financial, structural, operational, technological, and social behavioral barriers by Fletcher (2019). In the same study, it is emphasized that strategies involving stakeholders should be developed for the future. The proposed solutions can be listed as follows (Fletcher 2019):

- Making legal arrangements
- Developing strategies
- Collecting and processing data effectively
- Increasing the responsibilities of producers
- Ensuring international standardization
- Promoting innovative business models and eco-design
- Establishing relationships between sectors/stakeholders/disciplines
- Preparing the ground for industrial symbiosis
- Giving trainings to increase awareness in order to change consumption habits

In addition, it is anticipated that the transformation process will be facilitated by sharing knowledge and experience on an inter-sectoral and international scale.

The transition from the linear economy model, which has been implemented since the beginning of the industrial revolution, to the circular economy is still on-going (Yıldız 2019a, b). The process of transition to a circular economy on a global scale is progressing slowly due to difficulties and current implementation is only around 9% (Fletcher 2019). Today, the recycling rates of household wastes in the member countries of the EU vary regionally, changing between 5% and 80%, with an average of around 40% (EC 2015). Increasing this ratio is very important for the transformation to the circular economy model. With the circular economy practices adopted by EC in 2015, recycling and recovery rates increased within 1 year and an added value of nearly 150 billion € was obtained from these resources (Güngör 2019). With the transition to a circular economy, it is estimated that there will be around 1 trillion USD in 2025 (Romero-Hernández and Romero 2018).

The circular economy model, which will be advantageous in many areas such as economy, environment, and social areas, has started to be applied in different industries in many countries around the world. There are also studies on circular economy in the member states of the EU. The road maps that will make this transformation process more systematic and widespread are also specified in the circular economy action plan. Türkiye also has made considerable arrangements in its legislations through the EU integration process and has taken an important step in the transition to circular economy with the Zero Waste project. The transition process to the circular economy model, where resource management is very important, will be evaluated from the perspective of waste management and zero waste implementation in our country.

6.3 Current Situation of Waste Management in Türkiye

6.3.1 Country Profile

Türkiye is a transcontinental country located on the Anatolian peninsula in western Asia and a small enclave in Thrace in the Balkan region of Southeast Europe (Fig. 6.6). The Asian and the European sides are separated by the Bosporus, the Sea of Marmara, and the Dardanelles. The strategic geographical location of Türkiye between Asia and Europe gives a strategic power to the country. Türkiye is surrounded by seas in three sides including the Aegean Sea in the west, the Black Sea in the north, and the Mediterranean in the south, and also contains the Sea of Marmara in the northwest. The border neighbor countries are Greece and Bulgaria in the northwest, Georgia in the northeast, Armenia, Azerbaijan, and Iran in the east, and Iraq and Syria in the southeast. Türkiye is identified as a developing country, a regional power, and a newly industrialized country with its geopolitically strategic location.

The map of Türkiye is roughly in a rectangular shape with 1600 km long and 800 km wide, and lies between 35° and 43° N latitudes, and 25° and 45° E longitudes. Türkiye is the world's 37th-largest country with its land area of 783,562 square kilometers, 97% of which is located in the Asian side and 3% is located in the European side. The country is divided into 81 administrative provinces and these are further subdivided into districts, subdivisions, and villages. Istanbul, which straddles Europe and Asia, is the country's most populated city with almost 16 million population, while Ankara is the capital city. The gross domestic product (GDP) of Türkiye was around 750 billion U.S. dollars in 2019. Türkiye is the

Fig. 6.6 The location and the map of Türkiye. (From google images)

world's 19th largest economy and 13th largest by purchasing power parity (PPP). The country is among the founding members of the OECD and the G20.

The population of Türkiye is rapidly increasing with an average ratio of 1.83 and reached to around 83 million by the end of 2019 (Fig. 6.7). The most important parameter in the demographic change is the urbanization rate. While 75.8% of the population lived at rural areas and 24.2% in urban areas in 1927, today this ratio is almost reversed. The rate of the population living in rural and urban areas is calculated as 23.2% and 76.8%, respectively in 2011. The increase in the population and urbanization directly affects the waste generation rate and the amount waste. Therefore, waste management becomes a major problem especially in the urban

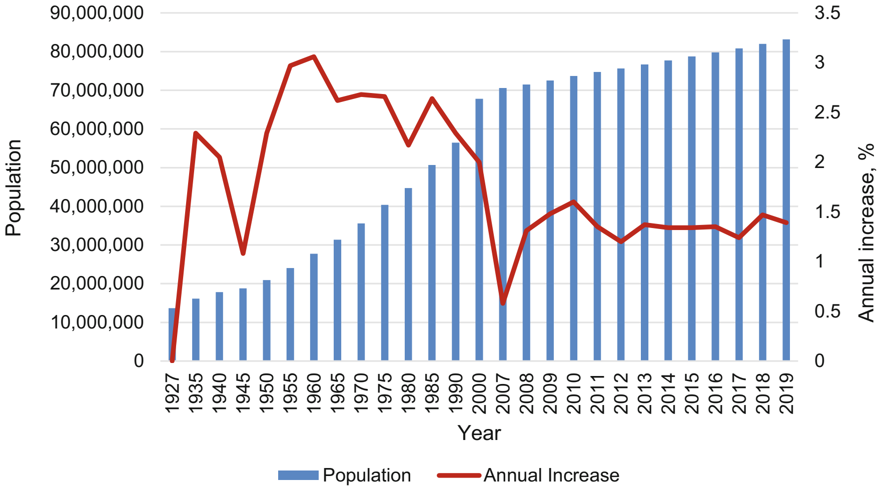

Fig. 6.7 Population growth an annual increase rate (TurkStat 2020)

areas. To solve this problem, the proposed sustainable integrated waste management system including waste prevention, waste reduction, reuse, recycling, energy recovery, and disposal methods must be flexible and convenient for the regional applications.

6.3.2 Background of Waste Management in Türkiye

The increase in the population results with some difficulties in the application of the sustainable waste management systems due to the increase in the amount of waste and the budget needed for the management of these waste (Guerrero et al. 2013). The annual amount of waste generated in 2018 was 32.21 million tons which corresponds to 393 kg/capita-year. In this section, the historical development of waste management applications in Türkiye from 1950s to date will be summarized.

The vast majority of generated waste disposed in dumping areas in the inland areas and into the sea in the coastal areas until this kind of disposal is forbidden in 1953, due to the environmental problems that occurred especially in shores. Solid wastes continue to be disposed of in uncontrolled dumping sites until 1993. The first sanitary landfill site, in accordance with technical standards including liner system, leachate collection and treatment and landfill gas management systems, was established in 1994 in İstanbul. Waste management systems including collection, recycling, composting, and landfilling spread rapidly after the year 2000 around the country.

Despite the history of waste characterization studies that lies to the early 1980s in Türkiye, the reliable data is available from the beginning of the 2000s. The Turkish Standards Institution (TurkStat) is in charge of collecting and reporting the statistics about economic, social, industrial, technological, agricultural, and environmental issues of the country and has been performing this task regularly since 2008.

The implementation of modern waste management technologies has a history of almost two decades in Türkiye. However, Türkiye has made a significant progress on waste management issues and shows great efforts to achieve successful results in recent years in this regard.

6.3.3 Municipal Waste Statistics and Characterization

Sustainable integrated waste management systems should have a hierarchy including waste prevention, waste reduction, reuse, recycling, energy recovery, and disposal. This section includes statistical information on the amount, characterization, and disposal technologies of municipal waste in Türkiye. The data given in this section is compiled from the "National Waste Management Action Plan – 2023" report published in 2017, which used the values from the Turkish Statistical Institution (TurkStat 2016).

Municipal wastes are defined as wastes that originate from residential areas or are in similar content from institutional sources and classified as non-hazardous wastes. Strategical planning and the success of the sustainable waste management system including collection, transport, recycle, and disposal methods depends primarily to accurate characterization which corresponds to the first step of waste management. Solid waste disposal without both material and/or energy recovery results with serious economic and natural resource losses. The increase in the waste generation reveals the need for the sustainable management of these wastes (Demir et al., 2020).

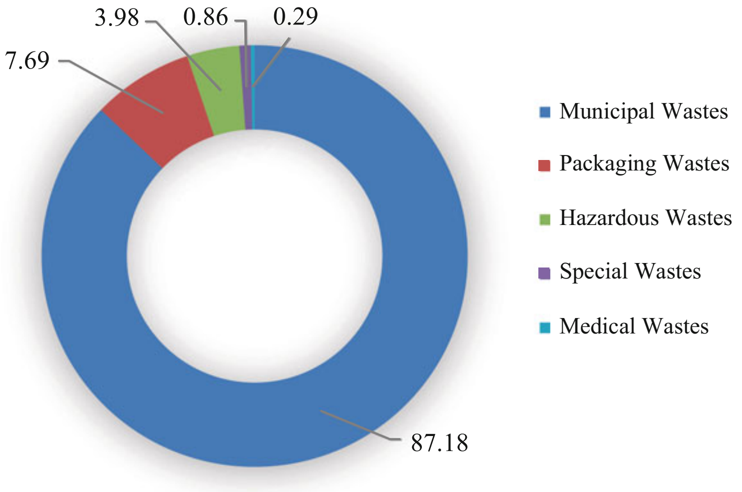

Fig. 6.8 Waste distribution in Türkiye (MoEU 2017)

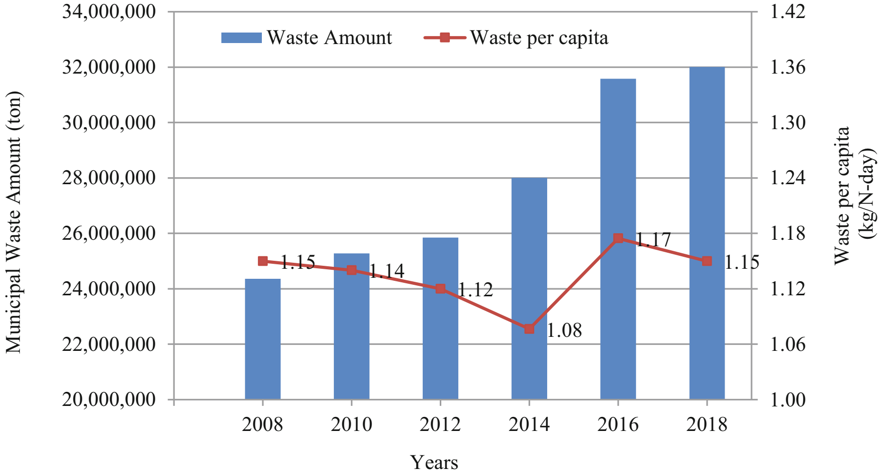

Fig. 6.9 Total waste amount and waste per capita (TurkStat 2020)

Figure 6.8 shows the classification of the waste sources in Türkiye. The largest group is municipal waste with an amount of 87.18% in the total waste stream. Packaging wastes, hazardous wastes, special wastes, and medical waste constitutes 7.69%, 3.98%, 0.86%, and 0.29% of the total waste amount respectively.

The amount of collected municipal solid waste (MSW) and the relevant waste generation rate between 2008 and 2018 are given in Fig. 6.9. The amount of waste generation per capita varies between 1.08 and 1.17 kg/day with an average of 1.13 kg/capita/day, according to the existing data. The increase in the recycling and reuse operations decreased the rate of waste generation as it is expected. Additionally, the increase in the number of citizens that receive waste services from municipalities causes the decrease of the waste amount per capita. The rate of the citizens living in urban areas and receiving services from a municipality increased from 70.5% in 2007 to 92.3% in 2016. Therefore, despite the increase in the amount of generated waste the amount per capita decreased gradually.

Several factors such as living standards, socio-economic development, and seasonal variations have an important effect on the characteristics of MSW. The average results of the waste characterization studies realized in 2016 are shown in Fig. 6.10. It is clear from Fig. 6.10 that organic waste constitutes the vast majority of total waste in Türkiye as it is the same for almost all developing countries.

Municipal solid waste management systems including dual collection for the recycling of packaging waste are progressing, but further developments are required in Türkiye. The Regulation of Landfilling of Solid Waste aims to decrease the landfilled biodegradable municipal waste amount in a scheduled period. In order to achieve this target, composting, mechanical-biological treatment, bio-methanization, and incineration plants are being evaluated for the source-separated organic waste streams. National waste management plans and action

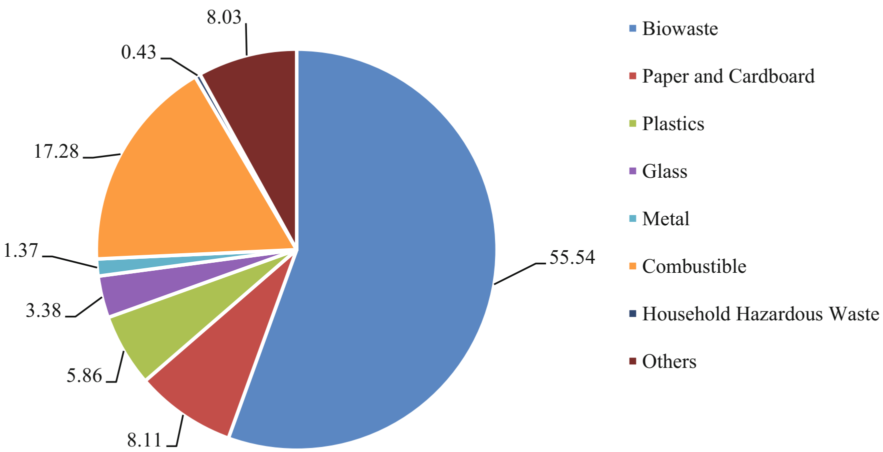

Fig. 6.10 Average MSW composition in 2016 for Türkiye, % (MoEU 2017)

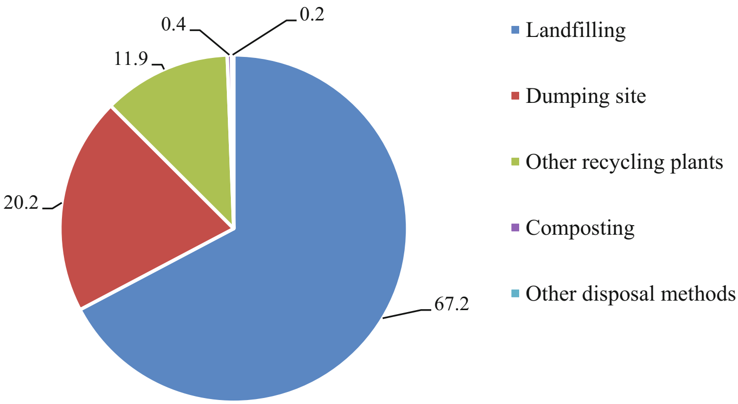

Fig. 6.11 Municipal waste management methods in Türkiye (TurkStat 2018)

plans give the details of these newly constructed plants and the required investment budget. The preparation and implementation of national strategies are completely under the responsibility of the Ministry of Environment, Urbanization, and Climate Change.

The distribution of waste management methods can be seen in Fig. 6.11. According to the data published for 2018 by the Turkish Statistical Institution, the rate of municipal waste sent to recycling in Türkiye is about 11.9%. There are six composting facilities, two bio-methanization plants, and eight mechanical and biological treatment plants in operation.

Landfill gas to energy plants are in operation in 29 provinces producing 900,000 MWh/year electricity. It is expected that the amount of electricity produced will increase depending on the increase in the number of landfills.

The final disposal of municipal wastes is performed by landfilling method. The collected amount of municipal waste has reached to 27.13 million tons with an increase of 11.4% since 2008. As of 2014, the number of landfills reached to 79, and 47.4 million people are served with these landfills.

6.3.4 Waste Management Legislations

Laws and regulations regarding environmental legislation are listed in Fig. 6.12, which also includes the chronological structure of waste management legislation in Türkiye.

Fig. 6.12 Development of waste management regulations in Türkiye. [1]Changed; [2]In force; [3]Repealed

The Environmental Law No. 2872 entered into force on August 11, 1983. It was inevitable to make changes in this Law over time and major changes were made in 2006. After the amendments, the purpose of the Law was regulated as "to ensure the protection of the environment, which is the common property of all living things, in line with the principles of sustainable environment and sustainable development".

The purpose of the Metropolitan Municipality Law (No: 5216) is to regulate the legal status of metropolitan municipalities and to ensure that the services are carried out effectively and efficiently. The part about solid waste in Article 7 of the Law defines the duties and responsibilities of metropolitan municipalities in line with the principles of sustainable development.

The first secondary level legislation on solid waste management is the Solid Waste Control Regulation issued in 1991. Within the scope of the regulation; For all kinds of solid waste (such as domestic, industrial, hazardous, special, and packaging wastes), reduction, collection, transportation, recycling, and disposal practices are included. Due to the difficulties experienced in the evaluation of all waste groups within the scope of a regulation, the number of secondary regulations according to waste types has increased over the years.

One of the most complex and costly aspects of EU accession processes is the Environment chapter. For full implementation, approximately 300 legislations must be updated and an expenditure of approximately 60 billion Euros must be made. It is foreseen that 12 legislative titles from the directives forming the EU acquis will be harmonized within the scope of waste management. With the rapid legislative updates in the last two decades, the necessary legislative changes have been mostly completed.

Currently, wastes are coded and classified according to the Waste Management Regulation (2015) established in accordance with the EU Waste Framework Directive (2008/98/EC). The regulation aims to ensure that wastes are managed from source to disposal without any impact on the environment and human health.

In the EU accession process, separate control regulations have been established for medical wastes, construction and demolition wastes, waste electrical and electronic equipment, used batteries and accumulators, end-of-life vehicles, end-of-life tires, mining wastes, PCBs and PCTs, and waste oils. In the accession process, all regulations will be harmonized with EU directives and deficiencies will be completed.

It is clear from the summarized regulations in this section that the Turkish Government has taken various measures to protect the environment and public health from inappropriate waste disposal. Great efforts have been made, especially in the last decade, to harmonize regulations in the EU accession process. The high investment costs of the required facilities for recycling, recovery, and disposal of wastes will be the most important factor that could have contributed to the failure of the implementation of the regulations.

The "Waste Management and Action Plan – 2023" prepared by the Ministry of Environment, Urbanization, and Climate Change in 2017 includes more reliable projections and investment costs for the waste sector compared to previous plans. Thus, it is expected that the regulations and investments, most of which have been harmonized with EU directives, will be completed by 2023 in accordance with the Waste Management Action Plan.

6.4 Zero Waste Project of Türkiye

Zero Waste is a new paradigm for waste streams and a method used for the development of the sustainable economy by "closing the loop". The stream is viewed as a valuable resource instead of a garbage in need for disposal. From this point of view, waste streams may represent feedstock for new products and a new economic opportunity (Matsch 2000). Zero waste is also a new design principle approach for waste management planning that emphasizes waste prevention rather than waste management and disposal. Therefore, zero waste planning involves new players except the local governments which are responsible for waste management traditionally (SCRD 2011).

Zero Waste system bounds public, business, and industry in a solid waste management program. Thus, one's waste becomes another's feedstock. Also, zero waste focuses on the prevention of pollution at source which means to create new local jobs in the community.

Although there are several definitions for "Zero Waste" throughout the world, zero waste has been defined as follows by the Zero Waste International Alliance:

> *Zero Waste is a goal that is both pragmatic and visionary, to guide people to emulate sustainable natural cycles, where all discarded materials are resources for others to use. Zero Waste means designing and managing products and processes to reduce the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them. Implementing Zero Waste will eliminate all discharges to land, water or air that may be a threat to planetary, human, animal or plant health.*

Significant developments in the recycling of municipal waste, which is one of the important points for a circular economy, were achieved by the Turkish Government. First lady Emine Erdoğan launched a nationwide Zero Waste Project in collaboration with the Ministry of Environment, Urbanization, and Climate Change in 2017. Through the project, within the framework of sustainable development principles, zero waste applications have started primarily in the Presidential Complex and the Ministry Building, in order to control waste generation and leave a clean and livable Türkiye and world to next generation (Güngör 2019). This section will give detailed information about the zero waste project of Türkiye.

6.4.1 Definition and Objectives of Zero Waste Project

Zero Waste Project of Türkiye is part of the harmonization with the EU and currently end of waste criteria are also being developed. The name of the project is called "*Sıfır Atık*" in Turkish, has become the name of one of the departments of the ministry and they published a zero waste policy regulation in 2019. The regulation obliges all municipalities, public and private institutions to provide a certain amount of waste separation facilities per area. Thus, it is aimed to increase the recycling rate of municipal solid waste to 35% by 2023. In addition, as of January 1, 2019, the practice of charging plastic bags has been introduced. Thus, the use of plastic bags has been reduced by 80%. Additionally, it is planned to implement a deposit application for bottles in the 2021–2023 period.

An Action Plan for the period of 2018–2023 has been prepared in order to spread the practice, which was initiated simultaneously in the service building of the Ministry of Environment, Urbanization, and Climate Change and the Presidential Complex. This plan is aimed to be implemented gradually in public institutions, terminals (airport, bus station, train station, etc.), educational institutions (university, school, etc.), shopping centers, hospitals, entertainment-recreation facilities (hotels, restaurants, etc.) where recyclable wastes are concentrated (Varır and Gürtepe 2018).

In this respect, it would be useful to consider the circular economy, which envisages the inclusion of production in the value chain in order to reuse waste from the design phase. Thus, the circular economy emerges as a method that can be applied not only in a specific sector such as waste management, but also in food, textile, tourism, transportation, and all other sectors.

The main purpose of the Zero Waste project, which is also supported by the Ministry of Environment, Urbanization, and Climate Change, is to use resources efficiently, to prevent or minimize waste generation, to prevent waste, to collect the waste separately according to their sources and to make these wastes a source of energy by recycling and thus to prevent health and environmental problems.

The disposal of wastes without being evaluated in the recycling and recovery process causes serious resource losses in terms of both material and energy. While the population and living standards in the world are increasing, there is an inevitable increase in consumption and this situation increases the pressure on our natural resources. and limited resources cannot meet the increasing needs. Therefore, the importance of the efficient use of natural resources becomes even more evident. That is why, in recent years, zero waste implementation studies have become widespread both individually, institutionally, and throughout the municipality (www.sifiratik.gov.tr).

6.4.2 Zero Waste Regulation

Zero Waste Regulation was published in the Official Gazette dated July 12, 2019 and numbered 30829. The Regulation covers the main principles regarding the establishment and monitoring of a zero waste management system and issuing a zero waste certificate to those who want to establish a zero waste management system.

The aim of the regulation is "to establish and develop zero waste management system in line with the principles of sustainable development with effective management of raw materials and natural resources". The following principles must be followed for the efficient use of resources in production, consumption, and service processes according to the regulation (Thornton 2019):

- Waste prevention according to the principles in the Regulation.
- Waste reduction if prevention is not possible.
- Assessments of the possibility of reuse regarding products and materials.
- Compliance with the implementation schedule for the implementation of the zero waste management systems.
- Reporting under the Regulation.

The Regulation obliges the buildings and campuses listed in Annex-1 of the regulation to establish a zero waste management system to comply with the general principles specified in the regulation. It is obligatory for the listed institutions and buildings to establish and implement a zero waste management system in line with the implementation schedule given in Table 6.2.

Within the scope of the regulation, there are four different zero waste certificates including basic level, silver, gold, and platinum zero waste certificates. It is obligatory to obtain basic level zero waste certificate for the buildings and premises which are obliged to establish the zero waste management system (Yıldız 2019a).

The Ministry of Environment, Urbanization, and Climate Change aims to prevent waste generation, reduce waste generation when it is not possible to prevent, and recycle waste in order to efficient use of resources with this regulation. The institutions and organizations mentioned in the regulation are required to establish a zero waste management system and comply with the provisions of the regulation.

6.4.3 Zero Waste Management System Implementation

According to the Zero Waste Legislation published in 2019, it is necessary to establish a zero waste management system that aims to protect the environment and human health and all resources in waste management processes in line with the effective management of raw materials and natural resources and sustainable development principles.

The Ministry of Environment, Urbanization, and Climate Change published a document for successful implementation to the Zero Waste Project for different institutions (MoEU, 2019). The general steps of the Zero Waste Management System are given below.

- **Determination of Focus Points:** *Persons who will be responsible for the establishment and implementation of the zero waste management system in the organization are determined. These people are also responsible for monitoring and reporting the system. They are also the people who will lead the team to ensure zero waste management.*
- **Determination of the Current Situation:** *The current situation regarding waste should be determined and analyzed, while applying the Zero Waste Management System.*
- **Planning:** *At the planning stage, the current situation is evaluated and a specific deadline plan is prepared.*

Table 6.2 Implementation calendar for zero waste management system

Group	Explanation	Deadline
Implementation schedule for local administrations		
Group I	• Metropolitan district municipalities	31 December 2020
	Population over 250,000	
Group II	• Metropolitan district municipalities	31 December 2021
	Population below 250,000	
	• Provincial, district, and town municipalities other than metropolitan areas	
	Central district municipalities	
	• Municipal associations	
Group III	• Provincial, district, and town municipalities other than metropolitan areas	31 December 2022
	Municipalities rather than central district municipalities	
	• Special provincial administrations	
	Out of contiguous area	
Implementation schedule for buildings and campuses		
Group 1	• Public institutions and organizations	1 June 2020
Group 2	• Industrial zones	31 December 2020
	• Airports	
	• Ports	
	• Business center and commercial plazas	
	Office/bureau capacity more than 100	
	• Shopping malls	
	Area greater than 5000 m^2	
	• Industrial facilities	
	• Educational institutions and dormitories	
	Those with more than 250 students	
	• Facilities with accommodation capacity of more than 100 rooms	
	• Health institutions	
	Greater than 100 beds	
	• Fuel stations and recreational facilities	
	• Sites with more than 300 residences	
	Grocery chains	
Group 3	• Shopping malls	31 December 2021
	1000–4999 m^2	
	• Business center and commercial plazas	
	Office/bureau capacity between 20 and 99	
	• Train and bus terminal	
	• Small Industrial facilities	
	• Educational institutions and dormitories	
	Those with students between 50 and 249	
	• Facilities with accommodation capacity between 50 and 99 rooms	

(continued)

Table 6.2 (continued)

Group	Explanation	Deadline
	• Health institutions	
	Bed capacity between 50 and 99	
Group 4	• Shopping malls	31 December 2022
	<1000 m^2	
	• Educational institutions and dormitories	
	Those with students <50	
	• Facilities with accommodation capacity of <50 rooms	
	• Health institutions	
	Bed capacity of <50	

- **Determination of Needs & Supply:** *All equipment that will be needed for all units in the institution (such as office, cafeteria, infirmary) is determined and supplied.*
- **Education & Awareness:** *After the equipment supply is completed, training and information studies are carried out.*
- **Implementation:** *Supplied collection equipment should be placed at easy access points for personnel. The prepared information posters are hung on the equipment so that they can be easily seen. Attention should be paid to the color scale on banners and posters.*
- **Reporting:** *As a result of the monitoring carried out by the work team during the reporting phase, deficiencies, if any, or the parties to be developed are determined and measures are taken.*

The Ministry has prepared guidelines for institutions, such as municipalities, shopping malls, hospitals, offices, establishments, marinas, schools, hotels, restaurants, residential sites, terminals and airports, and universities, that have the obligation to establish a zero waste management system. Although there are published guidelines for all of the above institutions, in this section the guide for the municipalities will be summarized.

6.4.3.1 Obligations of Buildings and Institutions Establishing a Zero Waste Management System

According to the Zero Waste Legislation, building and institutions that will establish a zero waste management system have obligations listed below.

Building and institutions that will establish a zero waste management system are obliged:

(a) To comply with the general principles specified in this Regulation in all activities
(b) To encourage all individuals and organizations within their areas of responsibility to separate their wastes by type and collect them separately

(c) To ensure the prevention/reduction of waste generation by working to prevent waste
(d) To create the infrastructure for the separate collection and temporary storage of wastes that are collected separately at source
(e) To comply with the implementation schedule defined in the Legislation in the establishment and implementation of the zero waste management system
(f) To carry out the necessary works and procedures in line with the guideline prepared by the Ministry for the establishment, operation, and monitoring of the zero waste management system and to integrate the existing waste management services into this system
(g) To determine the programs and policies for the integration of existing waste management services into the zero waste management system, including the transition to the zero waste management system, and reflect the relevant instructions
(h) To ensure that the entire process, starting from the design phase of the zero waste management system, including the monitoring of applications, is carried out in integrity and harmony with the participation of all persons and organizations within its area of responsibility
(i) To announce the established zero waste management system to all individuals and organizations in the area of responsibility, and ensuring that waste is collected in line with the established system
(j) To spread the zero waste management system and to raise awareness on this issue, by making awareness and training activities, by contributing and participating in activities organized within this scope
(k) To register in the Zero Waste Information System and to register the information and documents requested regarding the activities within the scope of the Regulation
(l) To report data on all wastes generated and separately collected and information on the places where these wastes are delivered twice a year, in January and July, through the zero waste information system

6.4.3.2 Guideline for Municipalities to Implement Zero Waste Management System

The general criteria for the municipalities that will implement the zero waste management system are given in Table 6.3. The following details are summarized from the zero waste project website (www.sifiratik.gov.tr).

The first step of the implementation of a zero waste management system in a municipality is to create a team that is responsible for the zero waste management system. This team ensures the establishment, development, improvement, effective, and efficient implementation and monitoring of the zero waste management system.

In the second step, collection infrastructure is established in order to collect wastes effectively. Within the scope of the dual collection system, blue and gray containers are used for recyclable waste and for other waste, respectively. Suitable waste collection centers were established and sufficient amount of waste glass collection boxes were placed to streets and avenues (Fig. 6.13). In addition, mobile

Table 6.3 General criteria for municipalities

1	Collecting recyclable paper, glass, metal, plastic wastes from residences separately with at least dual collection system
2	Placing collection equipment of sufficient number and capacity in easily accessible places on streets and public areas for dual collection system including recyclable wastes and other wastes
3	Placing sufficient waste glass boxes on avenues, streets, and public areas
4	Providing waste medicine collection equipment to the places where the drug is sold, which is determined as the collection point for the collection of waste drugs originating from the houses
5	Placing waste bins for the collection of textile/garment wastes and conducting studies to recycle these wastes
6	Establishment of Waste Collection Center/Centers and collection points in accordance with the principles determined by the Ministry
7	Determining the collection program for the collection of wastes and informing the public, and collecting wastes within the framework of this program
8	Planning, informing, and directing people about the wastes that can be collected at collection points and waste collection centers, such as waste batteries, waste oil, waste electrical and electronic equipment, waste medicine, and large volume wastes
9	Carrying out necessary studies for the recovery of biodegradable wastes by separate collection (compost, bio-methanization, etc.)
10	Recording the data regarding the zero waste management system applied in the area of responsibility
11	Carrying out awareness and awareness-raising studies on the implementation of the zero waste management system
12	Compliance with the Provincial Zero Waste Management System Plan

waste collection centers are established at easily accessible points (Fig. 6.13). Training and awareness-raising activities are organized to ensure that wastes can be collected effectively and efficiently within the scope of the zero waste management system. The public is informed about the collection model and where the wastes will be disposed of.

While waste collection activities are carried out by municipalities, it is ensured that wastes are collected from residential areas, workplaces, shopping malls, etc. within the scope of the dual collection system. Sufficient amount of collection bags and equipment are provided. Blue bags or equipment are used for recyclable waste and gray bags or equipment are used for other waste (Fig. 6.14). Collection activities are carried out separately from the blue and gray containers placed on the avenues and streets. The wastes that can be disposed of on the equipment found in the avenues and streets are indicated by letters and figures. The collected wastes are transported to licensed facilities to be recycled or disposed of (Fig. 6.15).

The last step in the implementation of the management system is the determination of the facility requirements. It is recommended that recyclable wastes be pre-treated in landfill sites. Mechanical sorting plants are used for recyclable materials. Also, bio-processing facilities, such as composting, bio-drying, and

Fig. 6.13 Waste glass collection boxes (**a**) and mobile waste collection center (**b**)

Fig. 6.14 Waste collection equipment in a dual collection system

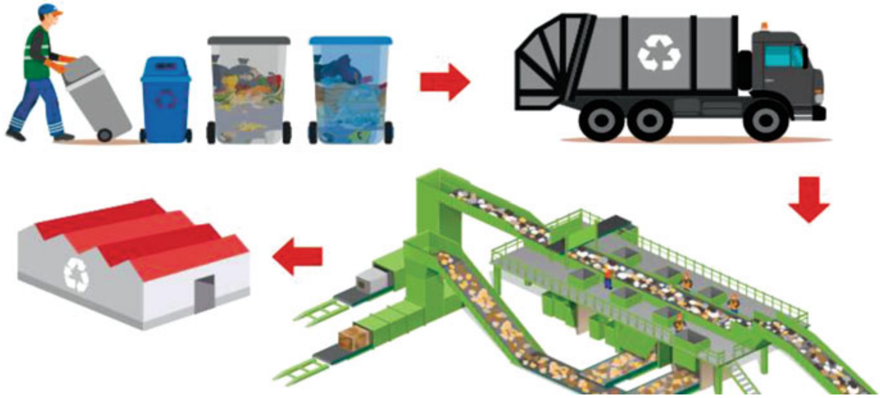

Fig. 6.15 Collection and transfer of wastes in a dual collection system

Fig. 6.16 Mechanical sorting and bio-processing of municipal waste

bio-methanization, are established in order to recycle biodegradable wastes (Fig. 6.16).

Zero Waste Project will be implemented gradually within the framework of the Zero Waste Management Action Plan, which includes the period 2018–2023. As of 2018, the Zero Waste Project was gradually implemented in

- Public institutions
- Terminals (airport, bus station, train station, etc.
- Educational institutions (university, school, etc.)
- Shopping centers
- Hospitals

- Have fun-rest facilities (hotel, restaurant, etc.)
- Big workplaces

and it is planned to be put into practice in all of Türkiye in 2023.

6.4.4 Contribution to the Circular Economy

Due to the negative effects of the linear economy that emerged after the industrial revolution on the environment, it has been understood that this approach is not a sustainable economic approach. As a matter of fact, the increased production as a result of industrialization has led to an increase in both resource consumption and waste. In this context, it is clear that the linear economy, which refers to the produce-use-throw system today, is not a sustainable economy model. In the current linear economy approach, raw materials are first processed and transformed into products. The system itself causes waste to be generated after it is used and converted into waste (Yıldız 2019b).

Linear economy is based on extracting resources, using the raw materials in production, the usage of products by consumers, and treating discarded products as waste (European Academies Science Advisory Council 2015). The circular economy approach is defined as a cleaner production approach that enables the reuse of products and raw materials with almost zero waste generation, where energy and all resources are used efficiently and waste is recycled in a holistic process.

In the circular economy, waste generation is prevented by transforming waste into a resource (Sapmaz Veral 2019). In this context, the circular economy can be identified as a new economic model that foresees radical changes in production and consumption habits. Due to the importance of the waste management issues, waste management is one of the first topics to be regulated in the EU environmental policy.

One of the most important requirements of waste management is the prevention of the damage to human health and the environment. The waste management hierarchy consisting of six stages comes into play in this context. According to the EU waste hierarchy, sorting from the most desired option to the least option is prevention, reduction, reuse, recycle, energy recovery, and disposal.

The primary goal of the zero waste project, which is a waste management philosophy, is to prevent waste generation to the lowest possible level, in order to succeed the efficient use of resources. In case of waste generation, the primary aim is to recycle waste to economy as raw materials and energy.

The EU advocates for the reduction of packaging waste by preparing the Toward a Circular Economy: Zero Waste Program in order to implement the zero waste plan within the circular economy. Both the EU and its member countries are working in the circular economy field. Türkiye is making significant efforts for the circular economy with its "Zero Waste" project.

6.5 Future Remarks

Environmental protection is one of the major priorities of all countries due to the increasing awareness. Waste management constitutes one of the major fields of environmental protection policies. Therefore, waste management strategies have become the basis of "sustainable development" and "circular economy" strategies, aiming to prevent waste generation and protection of natural resources for almost all countries.

As a member state to EU, environment is one of the most challenging sections in the accession negotiations for Türkiye. Environmental protection is regulated by nearly 300 Directives and regulations. Türkiye realized significant progress in the development of waste management since the beginning of the 1990s, which is further accelerated during the EU accession process after 2005. Besides the regulatory harmonization, the number of waste treatment, recycling, and disposal facilities are increasing with the aim of the environmental and human health protection. Türkiye has made a great progress in terms of both administration and implementation of the required facilities. In this respect, Türkiye has made significant progress at the point of both preparation of necessary regulations and establishment of the necessary facilities, in the last decade. The zero waste project is considered as the last step that will contribute to the transition to the circular economy throughout the country, and continues to be implemented successfully and spread rapidly.

6.5.1 Roadmap for Better Waste Management in the Scope of Zero Waste Project

Türkiye has made progress by harmonizing the waste-related regulations to EU directives and decreasing the municipal and hazardous waste amounts. However, most of the urban waste is still sent to landfills, and a very small part is composted or recycled. The government needs to go beyond waste management to adopt a comprehensive and specific material resources policy, while promoting the separate collection and recycling of different types of municipal solid waste.

Municipal solid waste is still almost completely disposed of in landfills in Türkiye. However, the number of uncontrolled landfills remains in high percentage. In order to establish a sustainable recycling economy or a circular economy in the country, the Turkish Ministry of the Environment and Urbanization has initiated the Zero Waste Project. The relevant regulation entered into force in 2019 and zero waste implementation efforts were scheduled. The zero waste project aims to establish a nationwide recycling system infrastructure. In addition, the project aims to raise public awareness on environmental issues, especially for recycling. The pilot phase of the project was initiated at the Ministry of Environment, Urbanization, and Climate Change Building and at the Presidential Complex in 2017. Türkiye wants to have the recycling system established nationwide by 2023.

In the last decade, MSW management in Türkiye has improved. The well-funded municipalities effectively organized the planning and implementation of the steps of

Integrated Solid-Waste-Management Plan. Most of the municipalities have currently intensified great efforts in the source separation of MSW. Landfilling, the last step of the waste management hierarchy, still remains the main disposal method. Landfill gas to energy is also not well organized. Although there have been many published studies showing the advantages of energy recovery from landfill gas, the application is still low and inefficient, probably due to high investment cost and operational problems. However, it is expected that the disposal or treatment methods such as thermal methods, bio-methanization, mechanical and biological treatment, and composting will be the main applications for the municipal solid waste management instead of landfilling in the near future.

The following recommendations can be listed for the development of the circular economy approach, which constitutes the basis of sustainable development:

- An integrated waste management hierarchy, which is the basic condition of sustainability, should be adopted and effectively implemented.
- The zero waste project, which will ensure the inclusion of waste into the regeneration process, should be expanded.
- Consumers should be encouraged to buy products with recyclable packaging in order to contribute to the integrated waste management system.
- Punishment and reward mechanism must be well operated in order to transform recycling into the lifestyle in the society. Thus, a recycling society, that prevents waste and uses the generated waste as a resource, can be created.
- Manufacturing industries should be encouraged to get maximum benefit from natural resources.
- Studies, that will raise public awareness about the advantages of the circular economy approach, should be carried out throughout the country.
- A country-specific circular economy action plan including the roadmap for the primarily industries should be prepared.

The increasing effort for the development of the circular economy by efficient use of natural resources will contribute to the sustainable development processes. The zero waste project of Türkiye is one of the most important studies that contribute to this goal.

6.5.2 Actions Required

Turkish government prepared several plans, including Solid Waste Master Plan, Waste Management Action Plan, National Recycling Strategy Document and Action Plan, and National Waste Management and Action Plan – 2023, in accordance with the EU environmental legislations.

National Waste Management and Action Plan (2016–2023) has been prepared in line with both the implementation of national legislations and harmonization with the EU acquis. The plan introduced the current situation of waste management system, including source separation, recycling, energy and/or material recovery,

Table 6.4 Plant capacities compatible with national strategies and estimated initial investment costs

Required facilities	Required capacity (ton/day)	Unit investment cost (€/ton)	Investment range (million €)
Recycling (Packaging Waste)	12,509	25–50	114.1–228.3
Biological Processes	4050	75–200	110.9–295.6
Mechanical-Biological Processes	7250	100–150	264.6–396.9
Thermal Processes	8046	300–450	881.0–1321.6
Landfilling	67,732	15–25	370.8–618.1
Total investment cost			1741.5–2860.5

and disposal methods, in 81 municipalities. Finally, the plan included the required types of facilities, capacities, and investment costs for waste management activities until 2023 on a regional basis with compliance to regulations.

Waste generation models used several indicators such as demographic structure, geographical characteristics, socio-economic status, tourism sector, agriculture and forestry, and livestock activities for the determination of waste generation tendencies. In accordance with these models, middle and long-term targets are listed as follows (MoEU 2017):

- Considering the amount of waste that will be produced in 2023; 35% of the waste will be recycled and 65% will be disposed in landfills. For this purpose
  – The amount of source-separated packaging waste must be increased from 5.3% to 12% in 2023.
  – The recovery rate of municipal wastes by biological methods must be increased from 0.2% to 4% by the end of 2023.
  – The rate of mechanical-biological treatment of municipal wastes must be increased from 5.4% to 11%.
  – The rate of thermal treatment processes must be increased from 0.3% to 8%.
  – The amount of the landfilled wastes must be decreased from 88.7% to 65% by the end of 2023.
- All of the open dumps will be closed and rehabilitated.
- Construction and demolition waste and excavation soil management will be ensured throughout the country.
- The efficiency of collection and recycling of special wastes will be increased.
- Additional facility investments will be increased for the recovery and disposal of hazardous wastes.

The required plant capacities and the estimated investment costs to achieve the targets of the National Waste Management and Action Plan – 2023 are summarized in Table 6.4.

In line with these strategies, new sanitary landfills are being built across the country. In addition, the EU Landfill Directive (99/31/EC) aims to reduce the rate of biological waste disposed of in landfills. In order to achieve this, it is aimed to establish mechanical biological treatment (MBT) and biogas facilities in metropolitan municipalities. In order for these facilities to be operated successfully, first of all, studies should be carried out to collect organic wastes separately at the source.

Due to the low calorific value of wastes and high investment and operating costs, thermal methods are not yet used in waste disposal in Türkiye. However, the number of incinerators is expected to increase in the near future in line with the objectives and strategies included in the National Plans. In addition, the widespread use of these methods will contribute to the goal of reducing the amount of organic waste going to landfills.

Türkiye has made great strides in establishing the legal infrastructure of waste management systems and improving practices in a short time. For this reason, it is believed that an effective waste management system will be established and many facilities will be built in Türkiye in the near future.

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Circular Economy Transition in EU and Italy in Key Priority Sectors: Policies, Initiatives and Perspectives

7

Patrizia Ghisellini, Renato Passaro, and Sergio Ulgiati

Abstract

In this work, we address the transition to the circular economy in the European Union (EU) and in Italy by focusing on the case of some value chains of products identified by the EU Circular Economy Action Plan for their significant environmental impacts. After a brief theoretical and political background on circular economy, the present study summarizes, with reference to the realities of the EU and Italy, the generation flows and recycling rates of municipal solid waste, total waste, packaging waste, plastic packaging waste, e-waste and food waste. The analysis is complemented by the evaluation of the circular practices of 32 organizations in Italy operating in the selected product value chains. The conclusions highlight the key results of the study and the main features of circular economy patterns at the macro and micro scales. The analysis highlights the emergence of two models: the recycling model (mainly applied at macro scale) and the circular economy practices model (repair, reuse, regeneration) applied at a micro and local scale with connections with the meso scale and the chain of supply.

Keywords

EU Circular Economy Action Plan · Municipal waste · Waste packaging plastic · WEEE · Food waste · Reduction · Reuse · Remanufacturing · Recycling

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7.1 Introduction

The circular economy (CE) as a model of economy aims to maintain the environmental value of products, materials and components in their life cycle at the highest levels and for as long as possible (Ellen Mac Arthur Foundation 2023; Webster 2021) making smarter and prudent the production and consumption activities and the overall society, aligning the latter with the imperatives of sustainable development (Holden et al. 2018). In that, the contribution of CE to sustainable development is increasingly recognized in many studies and at political level (Bauwens et al. 2020; Silvestri et al. 2020; Geissdoerfer et al. 2017; Ghisellini et al. 2016) where the CE is expected to contribute to face the global environmental challenges such as climate change and resource scarcity (The European and Social Committee 2019). In this regard, increasing resource efficiency (Tecchio et al. 2017) and extending the life cycle of products, components and materials help in reducing their environmental impacts (including CO_2 emissions) while maintaining to a higher extent their environmental value (Haupt and Hellweg 2019).

Circular design makes products that are more durable, or that could be easily repairable, upgraded or remanufactured helping saving natural resources (European Commission 2021). The overall environmental value of such resource-saving strategies can be very high as in the case of waste electrical and electronic equipment (WEEE) (Bressanelli et al. 2020; Baldè et al. 2017). Sustainable products also mean less impactful production and consumption activities and supply chains leading to further environmental, economic and social benefits to the economy and society (Walker et al. 2021). In that, the improvement of the stock of existing capitals (natural, social, cultural) beyond the economic and financial (Nogueira et al. 2019) helps in increasing the resilience of the society (Sucheck et al. 2021). Case studies of companies show how the adoption of eco-innovation oriented to CE leads to the creation of collaborations and resource exchange networks with other private or public companies or research centres as well as to the improvement of the social relations of businesses with citizens and employees favouring in some cases their reintegration into the labour market and into the production cycle (Ghisellini and Ulgiati 2020).

The New CE Action Plan adopted by the European Union (EU) identified key product value chains and related materials (electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients) as relevant for their environmental impacts and circularity potential. For these sectors, the urgency of taking actions is strongly encouraged by the EU, due to their potential contribution in achieving carbon neutrality by 2050 and the decoupling of economic growth from the use of natural resources (European Commission 2020). At the global level, the importance of adopting specific measures in some of these product value chains (e.g. metals, electronics and ICT, plastics, municipal waste, bioeconomy, construction) is also recently pointed out by other relevant think tank organizations as it would have the potential to reduce the GHG emissions by 39% to the year 2050 and contribute to maintain the average global temperature increase below 2 °C. This would imply the achievement of a global circularity rate by 17% compared to the current 8.6% (Circular Economy Network 2021).

In this chapter, we focus our attention on the waste flows of some these sectors (electronics and ICT, municipal solid waste including waste packaging and plastic waste packaging, food) that we have deeply investigated within the bilateral China-Italy High-Relevance Research Project funded by the Italian Ministry of Foreign Affairs and International Cooperation (years 2018–2020) and the Sino-Italian Cooperation Commission of the China Natural Science Foundation. We evaluate the adoption of CE principles (repair, reuse, remanufacturing, recycling) in these sectors in EU and in particular in Italy with the purpose of providing a state-of-the-art knowledge for the generation and management of these waste streams, their reverse cycles and supply chains, the preventive actions and strategies, main political tools and involved technologies and businesses for potential interest in Europe and worldwide.

7.2 Circular Economy Transition in the European Union

In this section, some of the relevant elements of the New EU CE Action Plan are summarized along with the presentation of the indicators that are proposed by the EU monitoring framework[1] to evaluate the progresses towards a circular economy. Finally, an overview of the main initiatives towards the transition to CE in Italy is presented.

7.2.1 The Circular Economy Action Plan

In 2015, the European Union adopted the First Circular Economy Action Plan with the aim of supporting the transition to the CE in EU and strengthening its global competitiveness in the CE. The latter was considered as an opportunity to transform the EU economy into a more sustainable one with new job opportunities for its citizens and green businesses for the companies. The Plan proposed a set of measures covering production, consumption, waste management, the take-up of secondary raw materials and water reuse as well as the legislation of waste.[2]

The New Circular Economy Action Plan[3] adopted in 2020 continues the political agenda of the First Action Plan for accelerating the circular economy

[1] Circular economy indicators, available at https://ec.europa.eu/eurostat/web/circular-economy/indicators. Last accessed: 10/06/2021.

[2] Closing the loop—An EU action plan for the Circular Economy, COM (2015) Final, 2.12.2015, available at https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF. Last accessed: 26/05/2021.

[3] A new Circular Economy Action Plan for a cleaner and more competitive Europe, COM/2020/98 final, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN. Last accessed: 25/05/2021.

(CE) transition[4]. Currently, the CE is also one of the core elements of the European Green Deal the recent and further political programme promoted by the EU aimed at tackling the climate and environmental challenges[5]. The New CE Action Plan considers the contribution of CE as crucial for achieving the climate neutrality by 2050 and decoupling economic growth from resource use. At the same time, the Plan also evidences the CE contribution in maintaining the competitiveness of the EU and its goals of perceiving an inclusive economic development. In fact: “The EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate in the coming decade” (p. 2).

The Action Plan highlights that the CE has the potential to provide benefits for all the actors of the society: companies, consumers, citizens and civil organizations. For companies, the adoption of more sustainable production models will increase profit opportunities and make them more resilient towards resource scarcity as well as on the price of material fluctuations. The role of digital technologies is emphasized in facilitating the strengthening of the industrial sector, the creation of new business models and the dematerialization of the economy contributing to reduce the EU dependence from primary raw materials. For consumers and citizens, the CE will provide “high-quality, functional and safe products, which are efficient and affordable, last longer and are designed for reuse, repair, and high-quality recycling. A whole new range of sustainable services, product-as-service models and digital solutions will bring about a better quality of life, innovative jobs and upgraded knowledge and skills will open up new job opportunities also at the local level and social integration”.

The Plan contains the different instruments to achieve its main goals centred in the creation of a market where sustainable products, services and business models have a highest share compared to the conventional linear products and consumption patterns and are oriented towards waste avoidance and minimization, as indicated in the upper options of the waste hierarchy scheme proposed by EU (Fig. 7.1). Besides identifying key product value chain, the Plan also anticipates the adoption of further measures to support the reduction of waste as well as the presence of a well-functioning internal market for high-quality secondary materials in the EU.

The role of Eurostat is emphasized as it should provide an easy access to the relevant data for citizens and policy makers in order to support (in particular for the latter) the monitoring process and the evaluation of the effectiveness of the adopted political actions, the main trends over time and their revision.

Within the EU, some member states (such as Italy, Germany, Poland, France, Spain, Greece, the Netherlands, Belgium, Portugal and Slovenia) have already

[4] https://ec.europa.eu/eurostat/web/circular-economy/overview.

[5] The European Green Deal, COM (2019) 640 final, available at https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF. Last accessed: 26/05/2021.

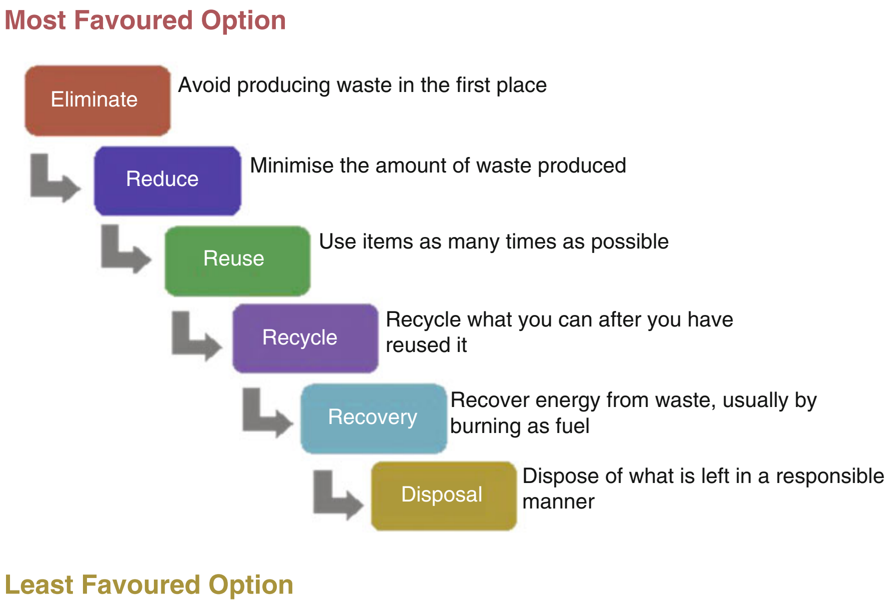

Fig. 7.1 Summary of the main options for waste treatment ranked according to their environmental sustainability in the so-called waste hierarchy

defined their CE strategy, while others are updating it (Finland) or are planning their CE strategy (Estonia). In overall, the CE strategies aim to support the transition to CE as well as coordinate the CE achievement with the global challenges including climate change, resource scarcity and the United Nations Millennium Development Goals (The European and Social Committee 2019)[6].

7.2.2 Circular Economy Indicator Framework

The monitoring framework of the EU for the CE transition considers a set of 15 indicators classified into 4 main areas (Table 7.1): production and consumption, waste management, secondary raw materials and competitiveness and innovation.

In this chapter, we will mainly focus on the "waste management" area by discussing the related indicators at European and Italian levels.

[6]See, for further reading on the CE strategies by the EU member states, the final report of the European and Social Committee, Circular economy strategies and roadmaps in Europe: Identifying synergies and the potential for cooperation and alliance building, available at https://www.eesc.europa.eu/sites/default/files/files/qe-01-19-425-en-n.pdf. Last accessed: 27/05/2021.

Table 7.1 Monitoring framework of the EU for the CE (Eurostat, Circular economy indicators, available at https://ec.europa.eu/eurostat/web/circular-economy/indicators. Last accessed: 27/05/2021)

Areas of the indicators	Indicators for the CE
Production and consumption	• EU self-sufficiency for raw materials
	• Generation of municipal waste per capita
	• Generation of waste excluding major mineral waste per GDP unit
	• Generation of waste excluding major mineral waste per domestic material consumption
Waste management	• Recycling rate of municipal waste
	• Recycling rate of all waste excluding major mineral waste
	• Recycling rate of packaging waste by type of packaging
	• Recycling rate of e-waste
	• Recycling rate of biowaste
	• Recovery rate of construction and demolition waste
Secondary raw materials	• Contribution of recycled material to raw material demand—end-of-life recycling input rates (EOL-RIR)
	• Circular material use rate[a]
	• Trade in recyclable raw materials
Competitiveness and innovation	• Private investments, jobs and gross value added related to circular economy sectors
	• Patents related to recycling and secondary raw materials

[a]The indicator measures the share of material recovered and fed back into the economy—thus saving extraction of primary raw materials—in overall material use. The circular material use, also known as circularity rate, is defined as the ratio of the circular use of materials to the overall material use. The overall material use is measured by summing up the aggregate domestic material consumption (DMC) and the circular use of materials. DMC is defined in economy-wide material flow accounts. The circular use of materials is approximated by the amount of waste recycled in domestic recovery plants minus imported waste destined for recovery plus exported waste destined for recovery abroad. Waste recycled in domestic recovery plants comprises the recovery operations R2 to R11—as defined in the Waste Framework Directive 75/442/EEC. The imports and exports of waste destined for recycling—i.e. the amount of imported and exported waste bound for recovery—are approximated from the European statistics on international trade in goods. A higher circularity rate value means that more secondary materials substitute for primary raw materials, thus reducing the environmental impacts of extracting primary material

7.2.3 Circular Economy Transition in Italy

Italy as an EU member state has started to support the transition to the EC since 2014 by first contributing to the preparatory stages of the First EU Action Plan on the EC and then by adopting the legislative instruments for its adoption at national level. As a matter of fact, the Commission for the Environment of the Italian Parliament approved several resolutions, and then the Italian government adopted the Law 221 of 28 December 2015, the so-called Collegato Ambientale, and further ministerial decrees and laws to promote the implementation of the CE in the country. The government has also funded research projects in particular areas such as the circular design of product, processes and services as well as the research and technologies for the recovery and recycling of waste electrical and electronic equipment (WEEE).[7] Moreover, the Ministry of the Environment has appointed a specific working group on both the CE and the efficient use of resources. In 2017, such group has also elaborated a strategic position document "Towards a circular economy model for Italy" that has been subject to public consultation.

The document provides a general overview of the CE and the strategic positioning of Italy with regard to the transition to CE in line with the commitments (adopted at EU level and G7 countries) established by the Paris Agreement on climate change and the United Nations 2030 Agenda on sustainable development. Moreover, the document underlines its centrality at national level being a key pillar of the National Sustainable Development Strategy contributing to the definition of the goals for an efficient use of natural resources and the adoption of more sustainable production and consumption models.

The general principles of the CE as well as the new concept of "circular economic system" are provided to appreciate the difference with the linear economic system. The purpose is to show how the circular economic system is embedded in the natural environment and the implications of such integration. In particular, the awareness of the environmental functions and services for the economy and society and their limits cannot be disregarded.

The document also emphasizes the role to businesses and industry but also of consumers that are required to actively and critically rethink their linear consumption models in favour of more sustainable and circular models. In this context, it is crucial to promote efficiency in the resource use and therefore their traceability.

Finally, the document deals with the economic tools needed on both the production side and the demand side, as well as how to transfer the tax burden in the new context of the CE. For the public sector, it stresses the opportunities derived from the adoption of the "Minimum Environmental Criteria" to render the important tool of Green Public Procurement more EC-oriented.[8]

Besides the institutional measures, there are many initiatives in the country oriented to adopt the CE at the micro, meso and macro scales in practice. Cities are including the principles of the CE in their urban regeneration policies[9]. Indicator's frameworks have been developed to monitor the transition to CE at urban level (Beccarello and Di Foggia 2020; Santagata et al. 2020). Three cities (Milan, Prato and Bari) have also been designated "pilot city" in a national project headed by the Ministry of the Environment for the experimentation on innovative

[7] Ministry for the Ecological Transition, Circular Economy in Italy, available at https://www.minambiente.it/pagina/leconomia-circolare-italia. Last accessed: 27/05/2021.

[8] https://www.minambiente.it/pagina/verso-un-modello-di-economia-circolare-litalia.

[9] New Prato, green city, available at https://www.cittadiprato.it/IT/Sezioni/480/Economia-circolare/. Last accessed: 07/06/2021.

Fig. 7.2 Graphical interface of the Atlas of the CE. (Source: Modified from https://economiacircolare.com/atlante)

actions on the CE and on all high environmental impact issues related to waste generation and treatment.[10]

At the micro scale, Italian companies increasingly see CE as a business opportunity to increase their competitiveness (Antonioli 2021; Bianchini et al. 2021; Chioatto 2021) rather than only a cost (Mura et al. 2020). This more positive attitude to CE is also showed by the increasing number of companies included in the Atlas of the CE since its creation in 2017. The latter is a web platform that gathers together the CE stories of organizations (private, non-profit, cooperatives, benefit corporation and so on) in order to share their information with citizens and promote collaboration between actors and the construction of "circular" supply chains based on the principles of sustainability and circularity. The web platform uses a map and specific cards (according to industry-based criteria) (Fig. 7.2) to help users identify individual organizations. The number of organizations is constantly updated with new Italian CE stories application in companies at the micro scale[11]. Moreover, also consumers/citizens show a positive attitude in engaging in circular behaviours that is also associated with an increase of their environmental awareness (Bianchini et al. 2021; Waste Watcher International Observatory 2020).

[10]Prato innovativa: green city, economia circolare, available at https://www.cittadiprato.it/IT/Sezioni/480/Economia-circolare/. Last accessed: 13/06/2021.

[11]CDCA, available at http://cdca.it/atlante-italiano-delleconomia-circolare/. Last accessed: 02/06/2021.

7.3 Municipal Solid Waste

In this section, we analyse the transition to CE in some of the key product's value chains evidenced in the EU Action Plan (electronics and ICT, packaging plastic and food). The analysis starts with municipal solid waste (MSW) and then widens on "plastic" as one of the relevant fractions of waste packaging composing MSW. After the analysis of MSW, the study evaluates the CE transition in waste electrical and electronic equipment (WEEE) value chain and finally in food supply chain.

7.3.1 Generation and Recycling of Municipal Solid Waste in EU

The most recent data from EUROSTAT evidence that the average amount of MSW generated annually per capita (pc) was 502 kg in EU, in the year 2019 (Fig. 7.3). The amount per capita (pc) changes across member states ranging from 280 kg/pc generated in Romania to 884 kg in Denmark. The latter with other countries shows an increasing trend in the period 2005–2019. On the contrary, Romania, Estonia, Hungary, Bulgaria, Sweden, Spain, Italy and the Netherlands evidence a decreasing trend of generated MSW per capita. These countries generated an amount of MSW pc similar or lower than the EU average. Italy generated 503 kg/pc in the year 2019 and occupies an average position in the EU. Besides economic development and consumption patterns, the amount generated is also affected by the collection and management of MSW.[12]

When it comes to the amount of waste and the different types of treatments (Fig. 7.4), the total amount of municipal waste landfilled has strongly declined over the years. In the period 1995–2019, such amount fell by 67 million tonnes, from 121 million tonnes (286 kg per capita) in 1995 to 54 million tonnes (120 kg per capita) in 2019. In that, the landfilling rate (landfilled waste as a share of generated waste) in the EU reduced from 61% in 1995 to 23% in 2019. The reduction is due to different factors including the adoption of two EU directives (Directive 62/1994 on packaging and packaging waste and Directive 31/1999 on the reduction of the amount of biodegradable waste going to landfill) and of the First Circular Economy Action Plan. The latter revised the legislative proposals on waste with a higher common target for the recycling of MSW and packaging waste and the reduction of landfilling for MSW[13].

The amount of MSW recycled (material recycling and composting) increased from 37 million tonnes (87 kg per capita) in 1995 to 107 million tonnes (239 kg per

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[12] There are differences between countries regarding the degree to which waste from commerce, trade and administration is collected and managed together with waste from households. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics#Municipal_waste_generation.

[13] European Parliament, The circular economy package: New EU targets for recycling, available at https://www.europarl.europa.eu/news/en/headlines/society/20170120STO59356/the-circular-economy-package-new-eu-targets-for-recycling. Last accessed: 10/06/2021.

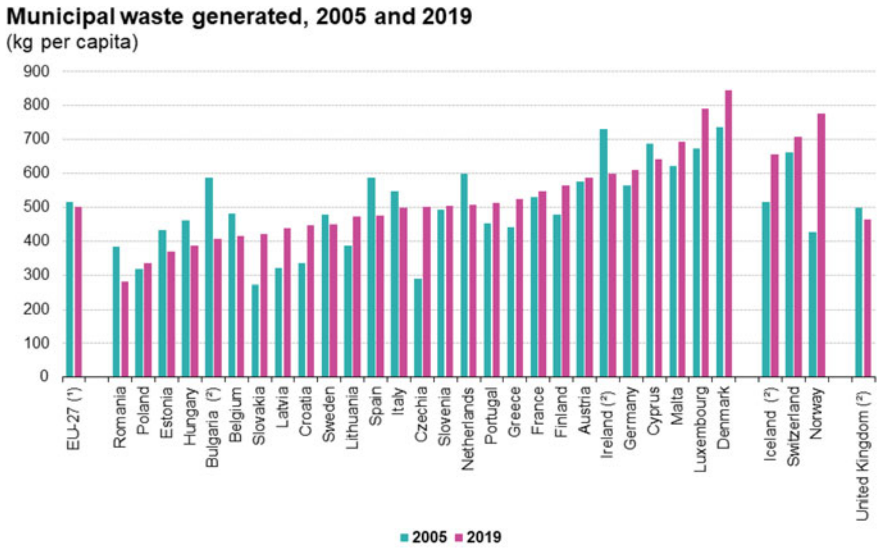

Fig. 7.3 Municipal waste generated per capita in the EU (years 2005 and 2019). Note: Countries are ranked in increasing order by municipal waste generation in 2019. (1) Estimated. (2) Bulgaria, Ireland and UK 2018 data and Iceland 2017 data. (Source: EUROSTAT (online data code: env_wasmun))

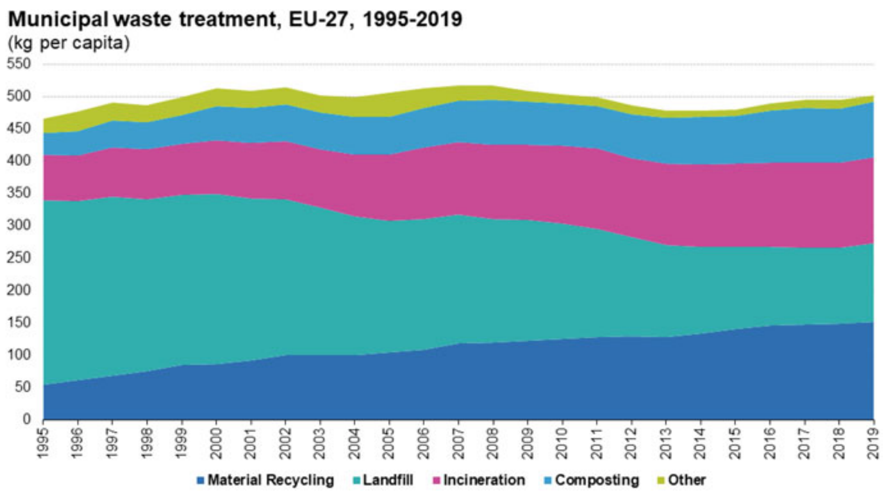

Fig. 7.4 Municipal waste by type of treatment in the period 1995–2019. Note: Estimated by Eurostat. (Source: EUROSTAT (online data code: env_wasmun))

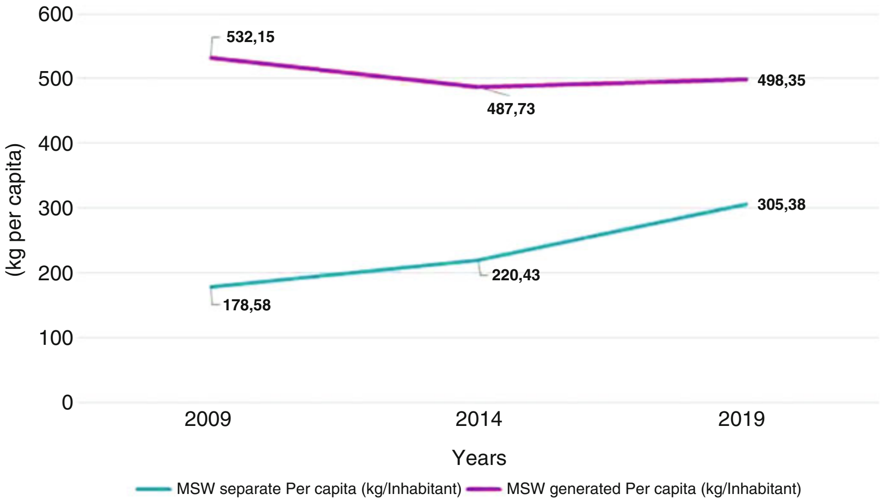

Fig. 7.5 Evolution of the amount of separate MSW and total MSW generated per capita in Italy. (Source of the data: ISPRA 2009, 2014, 2019)

capita) in 2019 at an average annual rate of 4.3%. In overall, the share of MSW recycled increased from 19% (year 1995), to 32.5% (year 2005), to 48% (year 2019).[14] With regard to the available data for Italy, the recycling rate increased from 18.5% to 51.4% from 2005 to 2019[15].

7.3.2 Generation and Management of MSW in Italy

The average national production of MSW per capita in Italy was 498.35 kg in the year 2019. Figure 7.5 shows that in the last decade, the trend of MSW generated per capita in Italy is decreasing, while the amount of separate MSW is increased over time shifting from 178.58 kg/per capita (year 2009) to 305.38 kg/per capita in the year 2019.

Across Italy, there are some differences between the geographical areas, with the Central Italy generating 543.12 kg per capita being well above the national average (Table 7.2). On the contrary, the average MSW generated in the southern area of the country is below the national average being 444.96 kg per capita. The average fraction of separate MSW that is collected and sent to recovery/recycling at national level is more than half of the total MSW generated (61.28% of the total MSW). Also,

[14]Municipal waste Statistics in the EU, available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics#Municipal_waste_treatment. Last accessed: 27/05/2021.

[15]EUROSTAT, available at https://ec.europa.eu/eurostat/databrowser/view/sdg_11_60/default/table?lang=en.

Table 7.2 MSW generated and separated in Italy at national level and in the three macro areas (north, centre and south). (Source of data: ISPRA, 2019)

Areas	Population (*n.*)	MSW separated (tonne)	MSW generated (tonne)	Percentage of MSW separated (%)	MSW separated (kg/pop.*year)	Per capita MSW gen. (kg/pop.*year)
North	27,774,970	10,021,294.61 tonne	14,398,682.47 tonne	69.6	360.8	518.4
Centre	11,986,958	3,761,965.27 tonne	6,510,345.53 tonne	57.78	313.84	543.12
South	20,482,711	4,614,058.82 tonne	9,114,005.34 tonne	50.63	225.27	444.96
National	60,244,639	18,397,318.69 tonne	**30,023,033.33 tonne**	**61.28**	**305.38**	**498.35**

The numbers in bold represent national data, while the other data pertain to specific areas of the country in this case, there are differences between the northern area of the country where on average 69.6% of the total waste are separated, whereas in the southern area, only 50.63% of the total MW are separated and sent to recovery/recycling (ISPRA 2019).

With regard to the different materials composing the total MSW generated in the year 2019, a share of 38% of MSW is still unseparated. The most relevant fractions that compose the separate share of MSW are organic (24%), paper and cardboard (12%), glass (7%) and plastic (5%).

7.3.3 Generation and Recycling of Total Waste in the EU and Italy

Total waste produced in the EU (27 countries) was 2,248,790,000 tonnes in the year 2004. The evolution shows that after a decrease in the year 2008 (2,144,700,000 tonnes), total waste slightly increased reaching an amount of 2,336,760,000 tonnes in the year 2018 (+3.9%) (EUROSTAT 2021)[16]. Italy also increased the amount of total waste from 139,806,106 tonnes (year 2004) to 172,502,773 tonnes (+23.4%) (year 2018) (EUROSTAT 2021)[17].

The analysis of these data by economic activities in the year 2018 evidences that the most relevant sectors were construction and demolition with a share of 35.9%, followed by mining and quarrying (26.6%), manufacturing (10.6%), waste and water services (9.8%) and households (8.2%), and the rest (9.1%) mainly involves services (4.2%) and energy (3.4%) sectors (Fig. 7.6).

On average, in the year 2018, in the EU, 55% of all waste excluding major mineral waste was recycled compared to the total (EUROSTAT 2018).[18] The EU recycling rate slightly increased from the year 2010 when it was 53% of total waste produced. Italy shows higher recycling rates compared to the EU average shifting from a recycling rate by 60% in the year 2010 to a recycling rate by 67% in the year 2018 (Fig. 7.7).

With regard to Italy, the available data in national statistics for the year 2018 of the amount of waste produced by the economic activities are summarized in Fig. 7.8. The wastes produced are classified on the basis of the specific chapter of the European List of Waste (Commission Decision, 2000/532/EC)[19]. Figure 7.8 shows that most of the waste generated comes from C&DW in chapter

[16]EUROSTAT, available at https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN/default/table?lang=en. Last accessed: 04/06/2021.

[17]EUROSTAT, available at https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN/default/table?lang=en. Last accessed:07/06/2021.

[18]EUROSTAT, Recycling rates of all waste excluding major mineral waste, available at https://ec.europa.eu/eurostat/databrowser/view/cei_wm010/default/table?lang=en. Last accessed: 04/06/2021.

[19]Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council (2014/955/EU), available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014D0955&from=EN. Last accessed: 27/05/2021.

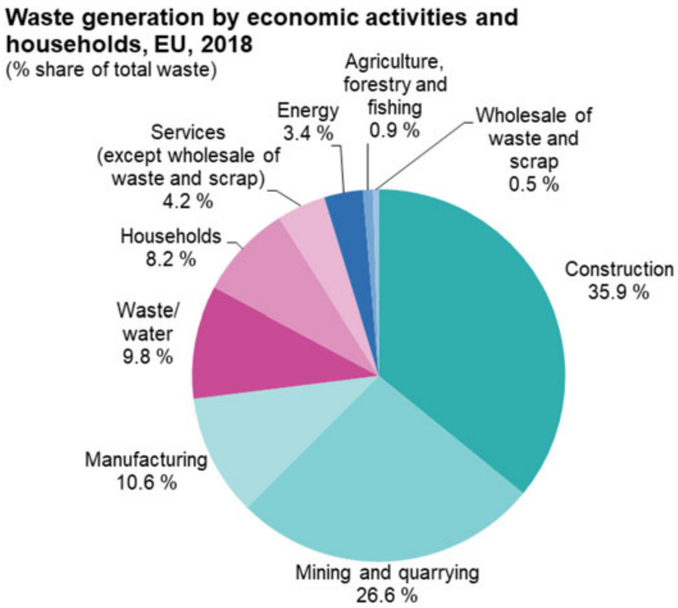

Fig. 7.6 Waste generation by economic activity in the EU (year 2018). (Source: EUROSTAT (online data code: env_wasgen))

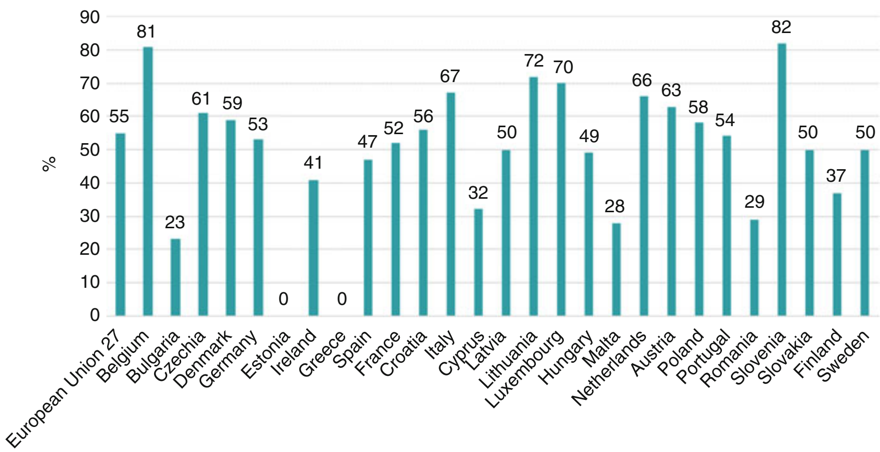

Fig. 7.7 Recycling rates of total waste excluding major mineral waste in the year 2018 in EU countries. (Source of the data: EUROSTAT 2018 (EUROSTAT, available at https://ec.europa.eu/eurostat/databrowser/view/cei_wm010/default/table?lang=en. Last accessed: 04/06/2021))

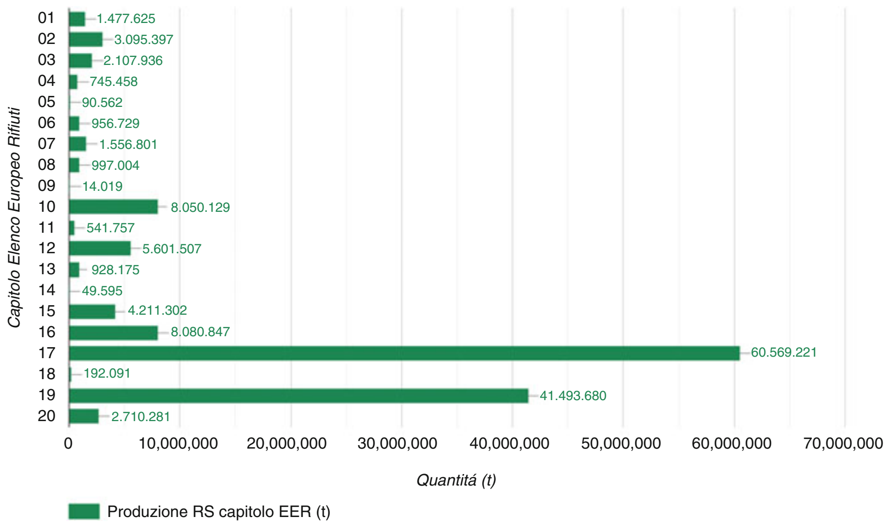

Fig. 7.8 Waste from all economic activities generated in Italy classified according to the chapter of the European List of Waste (vertical axes). (Source: ISPRA 2018 (National Cadastre of special waste, available at https://www.catasto-rifiuti.isprambiente.it/index.php?pg=prodrsnazione&aa=2018&atecocer=atecocer. Last accessed 04/06/2021))

17 (60,569,221 tonnes). Waste of the chapter 19 identifies waste from waste management facilities, off-site wastewater treatment plants and the preparation of water intended for human consumption and water for industrial use (41.493.680 tonnes), waste from thermal processes (chapter 10 with an amount of 8.050.129) and waste from chapter 12 including waste from shaping and physical and mechanical surface treatment of metals and plastic (5.601.507 tonnes).

In Italy, in accordance with the current legislation (Legislative Decree No. 152/2006), waste is classified on the basis of their origin as municipal waste and special waste. The latter category gathers waste coming from construction and demolition; agricultural, industrial and manufacturing activities; commercial services; and the recovery and disposal of waste from sanitary activities (ISPRA 2019). Moreover, depending on their dangerousness, waste is defined as hazardous and non-hazardous waste (ISPRA 2019).

The total special waste produced in Italy increased by 11% from 129.314.201 tonnes in the year 2014 to 143.479.702 tonnes in the year 2018 (ISPRA 2018)[20].

[20] National Cadastre of Special Waste, available at https://www.catasto-rifiuti.isprambiente.it/index.php?pg=prodrsnazione&aa=2018&atecocer=atecocer. Last accessed: 04/06/2021.

7.3.4 Generation and Recycling Rate of Packaging Waste in EU and Italy

Over the last decade, both the total and individual quantity of generated waste packaging in EU increased compared to the year 2008. After achieving a minimum in 2009 during the economic crisis with 149.9 kg per capita, the generated waste packaging increased almost every year achieving 174 kg per capita in 2018. The total quantity of generated packaging waste in EU was 77.7 million tonnes in the year 2018.[21] Figure 7.9 shows the amount of generated and recycled waste packaging per capita. The first indicator ranges from 67.8 kg/pc in Croatia to 227.5 kg/pc in Germany. Italy generated in 2018 an individual quantity (211.2 kg/pc) higher than the EU average (174 kg/pc). With regard to recycled waste packaging pc, Italy recorded in the year 2018 one of the highest recycled amounts with 140.1 kg pc, much higher than the EU average. In the period 2008–2018, the generated waste packaging pc in EU increased by 7.7%, while the recycled waste packaging pc increased by 18.2%.

In terms of packaging waste composition, Fig. 7.10 shows that "paper and cardboard" has by far the highest share (40.9%) in waste packaging materials

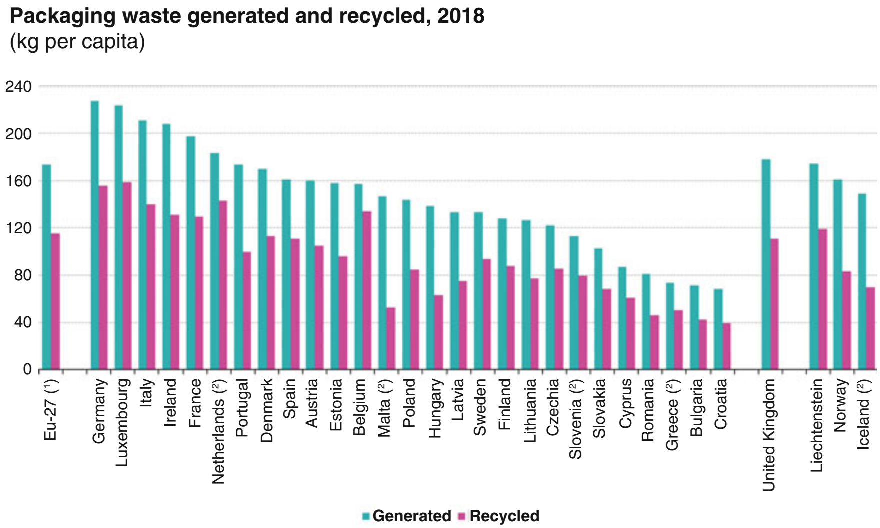

Fig. 7.9 Packaging waste generated and recycled in 2018. Note: Countries are ranked based on "Waste Generated". (1) Eurostat estimates. (2) 2017 data instead of 2018. (Source: EUROSTAT (online data code: env_waspac))

[21] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics.

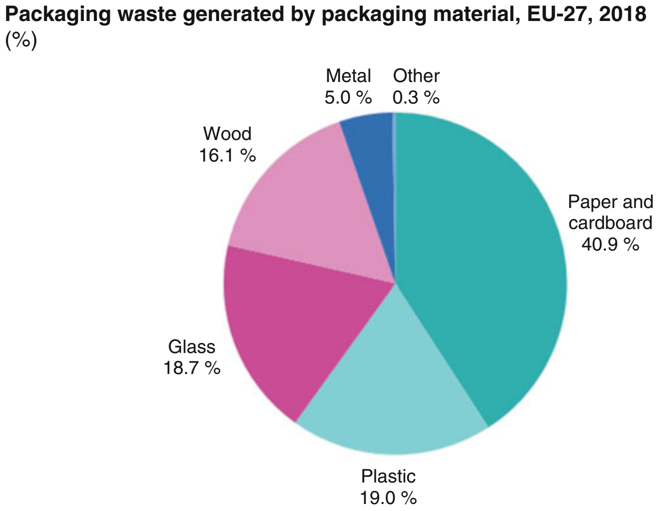

Fig. 7.10 Packaging waste generated by packaging material in the year 2018. Note: Eurostat estimates. (Source: EUROSTAT (online data code: env_waspac))

followed by "plastic" (19.0%), "glass" (18.7%), "wood" (16.1%) and "metal" (5.0%).

When it comes to the treatment for packaging waste after their use, the most common form in the EU is recycling including material recycling and other forms of recycling (e.g. organic recycling) (Fig. 7.11), while energy recovery represents a limited treatment.

The Article 6 of the Packaging Waste Directive (94/62/EC) defined the recovery and recycling targets for packaging waste by the year 2008 as well as the recycling targets by the years 2025 and 2030.

Figure 7.12 shows that in the year 2018, the target of 55% for the year 2008[22] set by the Packaging Waste Directive (94/62/EC)[23] was achieved by almost all of the member states except Hungary (46.1%) and Malta (35.6%, 2017 data). The Packaging Waste Directive (94/62/CE) sets a target of 65% to be met by 2025[24].

According to the latter, by 2025, the different packaging waste materials must be recycled as follows: 50% of plastic, 25% of wood, 70% of ferrous metals, 50% of aluminium, 70% of glass and 75% for paper and cardboard. The recycling rate for

[22] The Article 6 of the Directive 94/62/CE set that no later than 31 December 2008 between 55% as a minimum and 80% as a maximum by weight of packaging waste will be recycled.

[23] European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01994L0062-20180704&from=EN.

[24] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics#Waste_generation_by_packaging_material.

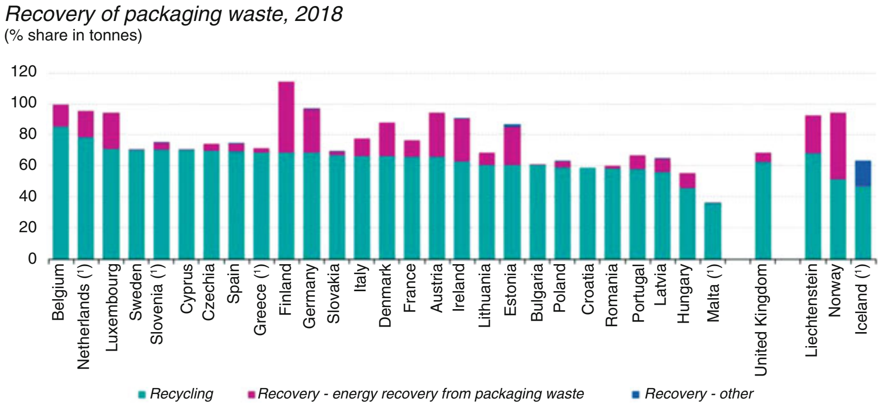

Fig. 7.11 Recycling and recovery of packaging waste in the year 2018 in EU. Note: Countries are ranked based on the share "Recycling". (1) 2017 data instead of 2018. (Source: EUROSTAT (online data code: env_waspac))

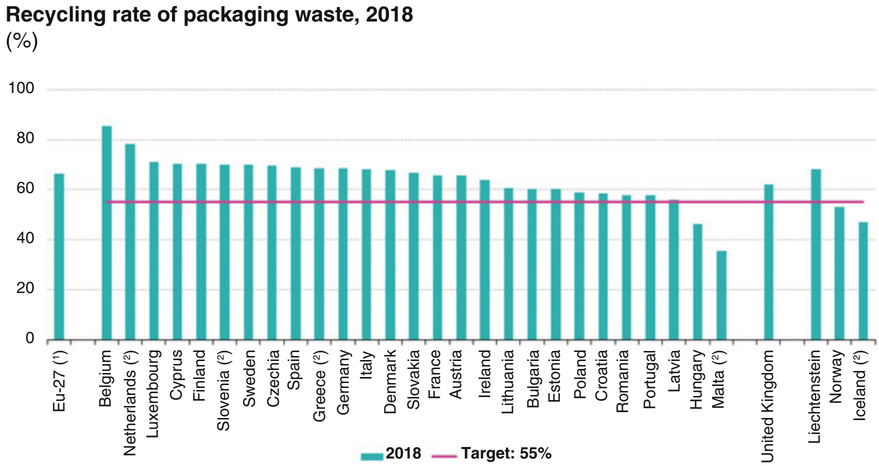

Fig. 7.12 Recycling rates of packaging waste for the EU countries and target of 55% set by the Packaging Waste Directive (94/62/EC). (1) Eurostat estimates. (2) 2017 data instead of 2018. (Source: EUROSTAT (online data code: env_waspacr) (EUROSTAT, available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics#:~:text=In%20the%20EU%2C%20the%20recycling%20rate%20of%20packaging,%25%20in%202008%20to%2080.9%20%25%20in%202018. Last accessed: 04/06/2021))

packaging waste for the EU 27 was 66%, while the one for Italy was a little higher being 68.3%.

The EU Action Plan evidences that the EC will review the Directive 94/62/EC by strengthening the mandatory essential requirements of packaging with the purpose of assuring the reusability/recyclability of all packaging in the EU market at viable costs. Moreover, other measures in the review of the directive that will be considered by the EC are those related to the following aspects:

- Reduction of overpackaging and packaging waste by setting targets and other waste prevention measures
- Strengthen of design for reuse and recyclability of packaging. Limits to the use of packaging for specific applications in particular in case of reusable products or consumer goods that can be provided safely without packaging
- Reduction of the complexity of packaging materials in terms of number of used materials and polymers
- Assessment of the feasibility of EU-wide labelling to enhance the correct separation of packaging waste at the source
- Definition of rules for the safe recycling for food contact materials made of plastic
- Monitoring and support of the implementation of the Drinking Water Directive and its requirements for making drinkable tap water accessible in public places and reduce the use of bottled water and prevent packaging waste

7.3.5 Recycling Rates of Plastic Packaging Waste in EU

Worldwide plastic waste is raising much concern due to the negative effects that its poor management and subsequent release have on the environment and human health. Deposits of plastics and microplastics are increasingly found in land, rivers and oceans[25]. Thus, an improvement of waste management including the associated infrastructure is essential to avoid that uncontrolled plastic waste will enter in the oceans from the land[26].

In EU, about 40% of whole plastic produced is mainly used as a raw material for packaging. The main types of plastic for packaging are polypropylene (PP), high-density polyethylene (PE-HD), low-density polyethylene (PE-LD), linear low-density polyethylene (PE-LLD) and polyethylene terephthalate (PET). At the end of life, plastic packaging waste is recycled as a material (42%) or undergoes energy recovery (39.5%), while the rest is landfilled (Plastic Europe 2020). With regard to the recycling rates of plastic packaging waste, the average in EU was 41.5% in the year 2018, while Italy recycled 44.6% of all plastic packaging waste (Fig. 7.13) (EUROSTAT 2018), and the rest was treated as energy recovery (43%) and landfilling (12.5%) (Plastic Europe 2020). It is important to mention that over the period 2006–2018, the plastic packaging waste sent to landfill strongly reduced from 883 kilotons (year 2006) to 287 kilotons (year 2018).

The EU lacks the capacity of managing the increasing amount of plastic waste generated in a circular and sustainable manner calling for the need to reduce its

[25] https://www.eea.europa.eu/publications/the-plastic-waste-trade-in.

[26] https://www.earthday.org/plastic-pollution-and-management-of-waste/.

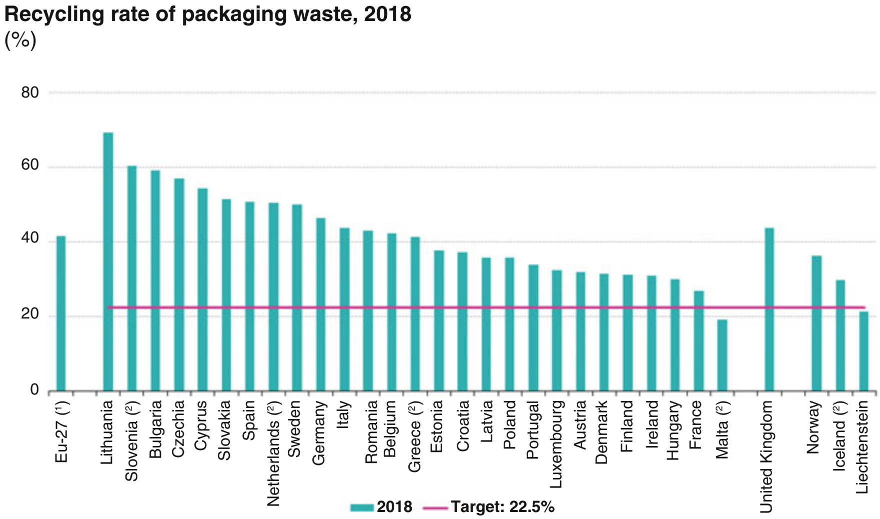

Fig. 7.13 Recycling rate for plastic packaging waste in EU. (1) Eurostat estimates. (2) 2017 data instead of 2018. (Source: EUROSTAT 2018 (online data code: env_waspacr))

generation[27]. The EU has also adopted in 2018 the "Plastic Strategy" that is an important part of the current CE Action Plan as well as of the whole EU Green Deal. Therefore, the CE contribution is also expected to be central in the achievement of the goals by 2030 of the Paris Climate Agreement, the Sustainable Development Goals and the EU's industrial policy objectives[28].

7.3.6 Collection and Recycling of Plastic Packaging Waste in Italy

In Italy, the collected plastic packaging waste comes from two different main flows: municipal waste and waste from economic activities (agriculture, industry and services). Municipal waste considers the collection of plastic packaging waste from the households. However, depending on the municipality, also part of the plastic packaging waste from services and industrial sectors are managed along with municipal waste from households. After the collection, the plastic packaging waste is sent to the selection plants and finally to the recycling plants. These two stages are also be managed by the Consortia such as "COREPLA[29]" if the

[27] https://www.eea.europa.eu/publications/the-plastic-waste-trade-in.

[28] https://ec.europa.eu/environment/strategy/plastics-strategy_en#:~:text=The%20EU%20adopted%20a%20European%20strategy%20for%20plastics,transition%20towards%20a%20carbon%20neutral%20and%20circular%20economy.

[29] COREPLA, National Consortia for the collection, recycling and recovery of plastic packaging waste, available at https://www.corepla.it/. Last accessed: 04/06/2021.

municipality has previously been involved in the Agreement with the Consortia. In the year 2019, about 35 selection plants and 77 recycling plants have treated the selected amount of plastic packaging waste generated in Italy. The plants for selection and recovery could also include the recycling. This "all-in-one" solution on the same industrial site is often the most suitable solution to maximize the resource recovery, as well as reduce the logistical, economic and environmental costs. However, the aspects related to specialization and the achievement of economies of scale are also taken into account to make very efficient the integrated systems (Italia del Riciclo 2020).

With regard to the market opportunities of recycled materials from packaging waste, the materials of the CPL family (Plastic Containers for Liquids) based on PET and HDPE are products with a consolidated quality with many and reliable applications. New technologies and experience in recycling make the market for materials derived from plastic waste packaging (flakes and granules ready for the "putting in the car") now essential for some applications. In particular, the recycled materials from CPL PET-based are now also used for the production of packaging for food use (trays and bottles). The recycling industry has developed decontamination and recovery processes that make recycled materials safe in contact with food (Italia del Riciclo 2020).

7.3.7 Scaling Up the Waste Hierarchy: Case Studies of Plastic Waste Packaging Reduction in Italy

The search of organizations by category "packaging" in the Atlas of the CE platform brings out 12 organizations. The evaluation of the circular practices and stories of such organizations evidences how the latter achieve in different ways the common goal of reducing plastic waste packaging. The different practices can be identified and grouped in the following:

1. Product substitution and expansion of the range of products to include packaging made of other materials than plastic:
   (a) **Cartonspecialist**: **biodegradable, compostable and recyclable products for the food sector**. The company produces food packaging products (dishes, glasses and other types of food packaging for take-away food) with lower environmental impact. The products are made of cardboard mono-material that is biodegradable, recyclable and compostable and are substitute of food packaging made of plastics[30].
   (b) **Napoletana Plastica: regenerated polyethylene bags for separate solid urban waste collection**. This company produces and distributes conventional and more sustainable bags and other products for urban separate

[30] Cartonspecialist, available at https://economiacircolare.com/atlante/cartonspecialist/. Last accessed: 03/06/2021.

collection made of plastic or biomaterials. The company also produces bags with a barcode that allows the traceability of waste contained in the bags from the urban collection stage (households) until the recycling stage. The production processes in the company is designed for the internal recycling of the scraps that become input for its products. Finally, the company organizes educational programmes for children aimed to promote best practices of recycling by means of laboratories of "eco-mosaic"[31].

(c) **Ecoplasteam: recycling of polylaminates in polyethylene and aluminium to produce EcoAllene, a secondary raw material**. This is a start-up that produces and distributes an innovative material named "EcoAllene" coming from the recycling of waste packaging materials used for producing food and drink packaging made up of polylaminates, PO-AL (plastic-aluminium) (well-known as "Tetra Pak"). Such containers were previously disposed of in landfills (as they are made of layers of cellulose, plastic and aluminium), incinerated or partially recycled by separating the three components. However, such process faces high cost and energy consumption and generates a low quality of the materials[32]. The innovative EcoAllene is a secondary raw material totally recyclable and is also certified "Remade in Italy", Class A[33]. The company also optimizes the use of energy and water. The water used in the process of cleaning of the raw material composing "EcoAllene" is reused, thanks to a purification and recycling system that allows the reuse of 50% of the water resource of the process of cleaning[34].

(d) **100% Campania: sustainable packaging in recycled cardboard**. It is a network of companies supporting the local recycling of paper waste for packaging and other products as well as the adoption of closed-loop cycles by the clients. This involves helping the latter to reuse or recycle their paper waste in closed-loop cycles. Since 2013, it has brought together six companies in a green district in the form of an integrated paper supply chain that offers packaging with a lower environmental impact in the whole life cycle. The latter starts from the recovery of waste paper to the finished product. The waste paper is sent to the paper mill of the network to be recycled and become, after a particular process, a new type of secondary raw material suitable for industrial use named "Greenpaper". The latter is then used for producing a new paper packaging "GreenboxX" made by the box factories of the network and distributed to their clients. GreenboxX is also FSC and EPD certified and communicates reliable and comparable data

[31] Napoletana Plastica, available at https://economiacircolare.com/atlante/napoletana-plastica/. Last accessed: 03/06/2021.

[32] Ecoplasteam, available at https://www.ecoplasteam.com/en/. Last accessed: 03/06/2021.

[33] Product Certification "Remade in Italy", product "EcoAllene", available at https://www.remadeinitaly.it/portfolio/ecoallene-ba20c05ap/. Last accessed: 03/06/2021

[34] Ecoplasteam, available at https://economiacircolare.com/atlante/ecoplasteam/#field-group-tab-4. Last accessed: 03/06/2021.

on resource and CO_2 savings, improving the transparency and the information available to the stakeholders about the environmental impacts and its origin in a local closed-loop recycling. The network also promotes the research and development of new types of materials and processes needed for the production of sustainable packaging, new market opportunities for the recycling of local pulp and develop sustainability projects whose goal is the progressive reduction of the GHG emissions and the environmental impacts of the participating companies and their products. Dissemination campaigns are used to inform citizens and institutions of the environmental and economic benefits for the territory of a local paper reuse/recycling cycle and encourage the quantity and quality of separate waste collection. All the companies of the network have one or more of the following certification schemes: ISO 9001 and 14001, SA 8000 (Social Accountability), FSC (Forest Stewardship Council), Environmental Product Declaration, Carbon Trust Standard and British Retail Consortium[35].

2. Product substitution and reduction of packaging per product:
   (a) **Bio al Sacco: a shop that minimizes waste generation, products without packaging and organic, short-chain products**. The food shop has been created with the aim of reducing packaging (and in particular plastic) and then waste. The shop also promotes organic agriculture, products coming from short food chains or zero kilometres as well as a daily menu (e.g. for breakfast) with quality products that are heathier and environmentally sustainable at affordable prices. The shop also participates to the European Week for Waste Reduction (EWWR) that is the biggest initiative in Europe favouring waste prevention by bringing together all the most social actors—citizens, schools, businesses, NGOs and associations—who organize activities to raise awareness about the importance of adopting waste reduction[36].
   (b) **Solo Peso Netto: shop of bulk products**. The shop has been founded in December 2017 with the aim of reducing in particular the use of packaging and plastic. Almost all the products in the shop are bulk and range from food products (such as pasta, rice, from legumes to cereals, honey) to liquid and solid household and personal hygiene products, as well as tea and herbal teas, spices, candies and pet food. Customers are encouraged to come to the store with their containers and reuse them in order to reduce the amount of waste packaging. Those who come to the shop without containers are provided with paper bags and containers for liquid products. Another key principle of the activity is quality, thanks to a careful selection of suppliers, which favours organic producers. The core business of "Solo Peso Netto" is the sale of bulk

[35] 100% Campania, available at https://economiacircolare.com/atlante/100-campania/. Last accessed: 03/06/2021.

[36] Bio al Sacco, available at https://economiacircolare.com/atlante/bio-al-sacco/. Last accessed: 03/06/2021.

products and partly local products from Tuscany. Customers can also purchase creams and toothpastes made in the laboratory of the shop and packaged in salvaged glass jars[37].

3. Product substitution and creative reuse:
   (a) **Palm Design: design products and containers from certified surplus wood**. The company focuses on the production of packaging products designed for upcycling or creative reuse after the end of life. For example, the wood and wine packaging line comprises containers, packaging and wooden objects handmade on the basis of the clients' requirements. The packaging products of such line are made of surplus wood (coming from a certified and legal supply chain), and after the first use, they can be reused for many other purposes adhering in this way to the principles of waste reduction and prevention[38].
4. Plastic packaging reuse:
   (a) **Scutaro Vincenzo & Figlio: industrial packaging and reuse**. The company sells industrial packaging (small tanks, plastic drums, plastic cans and iron drums) as well as restores them. The industrial packaging in plastic and iron are collected dirty from the clients, and after a washing process, they are reintroduced into the industrial market for a new reuse. All unsuitable packaging is recycled as a secondary raw material. The production process has also obtained its own patent. All the packaging of the company conform to the existing mandatory regulation (D.Lgs. 2005 n.152) including the technical standards for environmental labelling of packaging (UNI 10667) and the decisions of the European Commission[39]. The company has also adopted certification schemes such as ISO 9001/14001 and OHSAS 18001. Moreover, it also employs local workers and those falling into protected categories and promotes training and the continuous updating of safety standards in the workplace[40].
5. Academic research on waste packaging reuse:
   (a) **AWARE (Assessment on Waste and Research) academic research group: mapping of packaging reuse practices and research on waste management systems and technologies.** Besides the mapping of packaging systems, the research group also studies the environmental performance of waste management systems by means of the life cycle thinking approach and assessment methods (e.g. LCA). The current research performed by the AWARE team on behalf of the National Packaging Consortium consists in

[37] Solo Peso Netto, available at https://economiacircolare.com/atlante/solo-peso-netto/#field-group-tab-3. Last accessed: 03/06/2021.

[38] Palm Design, available at https://economiacircolare.com/atlante/palm-design/. Last accessed: 03/06/2021.

[39] Vincenzo Scutaro e Figlio, available at http://www.scutarosrl.com/etichettatura-ambientale-imballaggi/. Last accessed: 11/06/2021.

[40] Vincenzo Scutaro e Figlio, available at https://economiacircolare.com/atlante/scutaro-vincenzo-figlio/#field-group-tab-3. Last accessed: 03/06/2021.

the mapping and the environmental assessment of reusing packaging. This option is considered in the waste hierarchy as a preferable solution to recycling in terms of reduction of the amount of waste generated and increase of the efficiency in the use of natural resources. The project aims above all to collect uniform and reliable data on the reuse of packaging in the Italian context and propose guidelines for the continuous monitoring of the system. The analysis considers packaging of any materials that can be reused in the business-to-business or business-to-customer contexts after a possible recovery process[41].

7.4 Waste Electrical and Electronic Equipment (WEEE)

WEEE comprises a wide range of materials of different economic and environmental values. Estimates evidence that about 60% of their weight is made of rare earth metals (lanthanum, cerium, praseodymium, neodymium, gadolinium and dysprosium); precious metals including gold, silver and palladium and other metals with high intrinsic value (such as copper, aluminium or iron); plastics (about 15% by weight); and glass (Ibanescu et al. 2018; GWMO 2015). The valorization of these materials in a sustainable manner (compared to the disposal in landfills or waste to energy) (Remedia 2019) provides relevant benefits for the environment and the economy (Bressanelli et al. 2020; Ibanescu et al. 2018). WEEE also contains toxic materials and metals[42] (European Commission 2019a, b) and for this reason should be properly managed as it could be a source of risks for human health and the environment (Perkins et al. 2014).

The EU has adopted two relevant directives (the WEEE Directive and RoHS Directive) in order to regulate and improve the management of WEEE. Both directives have undergone a process of revision over time on the basis of the proposal of the European Commission (European Commission 2019a). The first WEEE Directive (Directive 2002/96/EC), which entered into force in February 2003, contributed to the creation of WEEE collection schemes (free of charge for the consumers) with the purpose of increasing their reuse or recycling[43] (European Commission 2019a, b). In 2008, the European Commission proposed to revise the first WEEE Directive to address the fast-increasing WEEE stream. The new WEEE

[41] AWARE, available at https://economiacircolare.com/atlante/aware/#field-group-tab-2. Last accessed: 03/06/2021.

[42] Toxic materials contained in WEEE include, e.g. brominated flame retardants from plastics; lead-containing glass; ozone-depleting substance as chlorofluorocarbons contained by cooling agents from refrigerators/air conditioners as well as toxic metals, cadmium, copper, lead and chromium; and persistent organic pollutants (dioxins, dibenzofurans, polyvinyl chloride, polycyclic aromatic hydrocarbon) (Ibanescu et al. 2018).

[43] Directive 2002/96/EC, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002L0096.

Directive 2012/19/EU entered into force on 13 August 2012 and became effective on 14 February 2014[44]. Its overall aim, underlined at the Preambular paragraph 6 of the directive, is "to contribute to sustainable production and consumption by, as a first priority, the prevention of WEEE and, in addition, by the re-use, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials. It also seeks to improve the environmental performance of all operators involved in the life cycle of Electrical and Electronic Equipment, e.g. producers, distributors and consumers and, in particular, those operators directly involved in the collection and treatment of WEEE" (Directive 2012/19/EU).

The first RoHS Directive (2002/95/EC) was aimed to limit the use of hazardous substances in electrical and electronic equipment, and in particular cases, heavy metals (lead, mercury, cadmium and hexavalent chromium) and flame retardants (polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)) required their substitution with safer alternatives[45]. The RoHS 2 Directive 2011/65/EU[46] has been introduced on the basis of the proposal of the European Commission on December 2008 becoming effective on 3 January 2013. Further, in January 2017, the Commission adopted a legislative proposal to introduce adjustments in the scope of the RoHS 2 Directive, supported by the impact assessment. The respective legislative act amending the RoHS 2 Directive, adopted by the European Parliament and the Council, has been published in the Official Journal on 21 November 2017 (European Commission 2019b)[47].

The WEEE Directive 2012/19/EU covers all electrical and electronic equipment (EEE) (extended to photovoltaic panels) used by consumers and EEE intended for professional use.[48] Until 2015, the minimum collection target (4 kg/per capita/year) only regarded WEEE from private households, whereas from 2016 onwards, the collection target covered both types of WEEE: from households and other subjects[49] (European Commission 2014).

The Directive 2012/19/EU, among others, established minimum collection rates for WEEE in EU. These have been transposed in Italy with the Decree

[44] Directive 2012/19/EU, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0019.

[45] RoHS Directive 2002/95/EC, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002L0095.

[46] RoHS 2 Directive 2011/65/EU, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0065.

[47] http://ec.europa.eu/environment/waste/rohs_eee/index_en.htm.

[48] From 15 August 2018, subject to paragraphs 3 and 4, to all EEE. All EEE shall be classified within the categories set out in Annex III. Annex IV contains a non-exhaustive list of EEE which falls within the categories set out in Annex III (open scope).

[49] "commercial, industrial, institutional and other sources which, because of its nature and quantity, is similar to that from private households", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02012L0019-20180704, last accessed: 11/06/2021.

49/2014 (Decree Law 49 2014)[50], and the Art. 14 underlined the following target set by the directive:

- By 31 December 2015, an average rate of WEEE collected from households equal to 4 kg/per capita/year should have been achieved.
- From 1 January 2016 a minimum rate of 45% of WEEE collected calculated on the basis of the total weight of the WEEE collected in a given year and expressed as percentage of the average weight of EEE products put on the market in the three preceding years. From 1 January 2016 to 31 December 2018, the amount of WEEE collected should increase gradually to achieve the final rate of collection indicated for the year 2019.
- From 2019 the minimum rate of 65% of the average weight of EEE products put on the market in the three preceding years or in alternative should be achieved a minimum rate by 85% of the weight of WEEE produced at national level.

Figure 7.16 shows total collection rates in the year 2017 as a share of the EEE put on the market in the EU. From the reference year 2016 onwards, the annual collection target is defined “as the ratio between the collected amount and the average weight of EEE put on the market in the three preceding years”[51]. “The collection target is set at 45% for reference year 2016 (as reported in 2018) and will rise to 65% for reference year 2019 (to be reported in 2021)”[52]. The collection rates in Fig. 7.14 are calculated as the ratio of the amount of collected WEEE in 2017 in relation to the average amount of EEE put on the market in the three preceding years as, for example, 2014–2016. The collection rates calculated for each one of the EU member states allow the comparison with the two targets of 45% and 65% set by the WEEE Directive (2012/19/EU). The data show that more than half of the EU member states (Bulgaria, Croatia, Estonia, Sweden, Hungary, the UK, Ireland, Portugal, Slovakia, Luxembourg, Czechia, Austria, Denmark, the Netherlands, Finland, Poland, France and Germany) had collection rates beyond the 45% target in 2017, while Italy and other countries, such as Lithuania, Belgium, Greece, Slovenia, Romania and Malta, were below the 45% target. Moreover, Bulgaria and Croatia by reaching an amount of collected WEEE of 79.4% and 81.6%,

[50] The Decree 49/2014 by transposing the Directive 2012/19/EU further promotes the principle of producers’ responsibility for the management of WEEE (that was also carried out in the previous Decree 151/2005) that applies to the first (producer, importer or distributor) who put on the Italian territory the EEE. Responsibility entails the financing and management of the recovery and recycling system of the WEEE. As such, the responsibility ends up only when WEEE are treated adequately and transformed into secondary materials. However, the responsibility of the producer is collective as it is proportional to the market share of the producer. Consequently, producers have created the collective systems that are associations of producers (Remedia 2019).

[51] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment#EEE_put_on_the_market_and_WEEE_collected_in_the_EU.

[52] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment#EEE_put_on_the_market_and_WEEE_collected_in_the_EU.

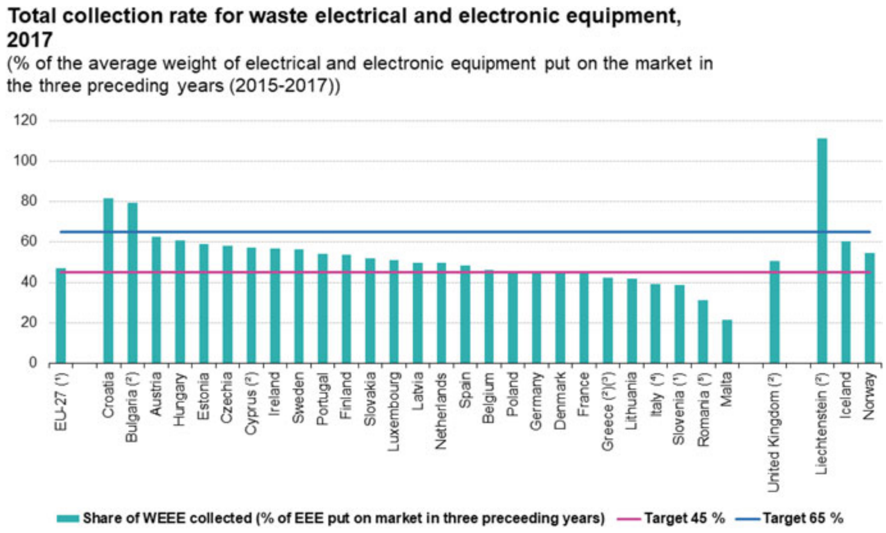

Fig. 7.14 Total collection rate for waste electrical and electronic equipment in 2017 as a percentage of the average weight of EEE put on the market in the three preceding years (2013–2015) (%). (1) Eurostat estimates. (2) Definition differs. (3) Estimate. (4) Data on collection 2015 instead of 2017; % of average weight of EEE put on the market 2013–2015. (5) Data on collection 2016 instead of 2017; % of average weight of EEE put on the market 2014–2016. (Source: EUROSTAT (online data code: env_waselee) (available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment#EEE_put_on_the_market_and_WEEE_collected_in_the_EU))

respectively, had already reached in 2017 the new 65% target that became effective from the reference year 2019 onwards.

7.4.1 E-Products Put on the Market and Generation and Recycling of WEEE in the EU

Figure 7.15 shows the amount of EEE (such as computers, TV sets, fridges and cell phones), sold in the last decade in EU (EUROSTAT 2017). The sold EEE has grown rapidly due to the continuous and fast development of new technologies and the attitude of consumers to devote larger shares of their income to buy hi-tech products of the last generation (Ecolight 2019; Isernia et al. 2019). The lifetimes of EEE products have also reduced dramatically over the years (Bhutta et al. 2011). The amount of EEE put on the market in the EU was 7.3 million tonnes in 2013. From such year onwards, the amount of EEE put on the market strongly increased, reaching 9.0 million tonnes in 2017 (+24.1%). More or less the same trend can be observable for WEEE being collected, treated or recycled or undergoing to energy recovery.

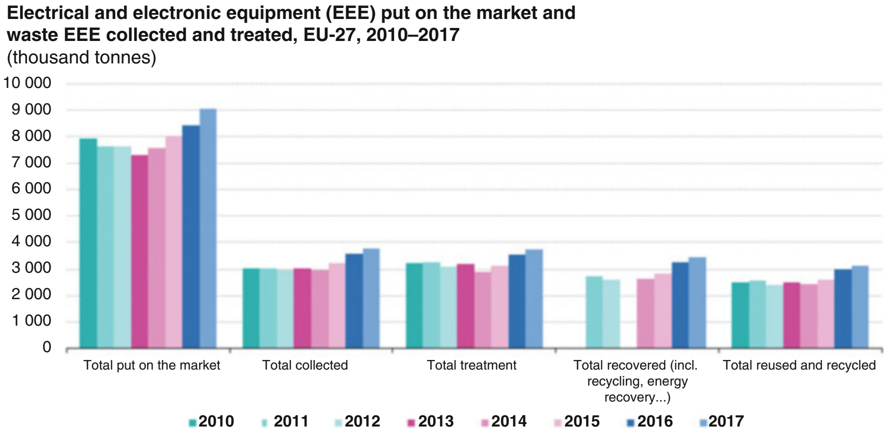

Fig. 7.15 Evolution of the amount of EEE put on the market and waste EEE collected and managed in the EU. Note: 2010, 2016 and 2017 data, as well as 2011 data for reused and recycled EEE waste: Eurostat estimates. (Source: EUROSTAT (online data code: env_waselee))

As for the recycling rates for WEEE, in the EU 27, it was 27.9% (year 2010) and 38.9% (year 2018), while for Italy, it was 27.8% (year 2010) and 32.1% (year 2015 as the latest available data) (EUROSTAT 2018)[53]. The recycling rates for both the EU and Italy increased over time.

An important aspect of WEEE management in EU is the relevant heterogeneity among member countries. Figure 7.16 shows how the WEEE collection rates per capita change across EU ranging from 2.4 kg per capita in Romania (year 2016) to 14.1 kg per capita in Sweden and 18.7 kg per capita in Norway. In 2016, compared to 2008, the total amount of collected WEEE per capita changed substantially for some countries such as the UK that almost doubled the collection rate as well as Liechtenstein. On the other side, some countries such as Italy reduced the amount of WEEE collected shifting from 7.6 kg to 6.3 kg per capita in 2017, resulting in below the EU 27 average in 2017 (8.4 kg per capita).

Finally, Fig. 7.17 shows the composition of WEEE collected into the main EEE categories. In the year 2017, the category "Large household appliances" has a share of 51.8% compared to the total WEEE collected (accounting 1.9 million tonnes). Then followed "Consumer equipment and photovoltaic panels" (14.8%) and "IT and telecommunications equipment" (14.6%) accounting about 555,000 tonnes and 547,000 tonnes, respectively, and "Small household appliances" contributed almost 383,000 tonnes and a share of 10.2% of total collected WEEE in the EU in 2017. The last category, "Other waste EEE", totalled almost 327,000 tonnes, corresponding to a share of 8.7% of WEEE collected.

[53]EUROSTAT, available at https://ec.europa.eu/eurostat/databrowser/view/cei_wm050/default/table?lang=en. Last accessed: 04/06/2021.

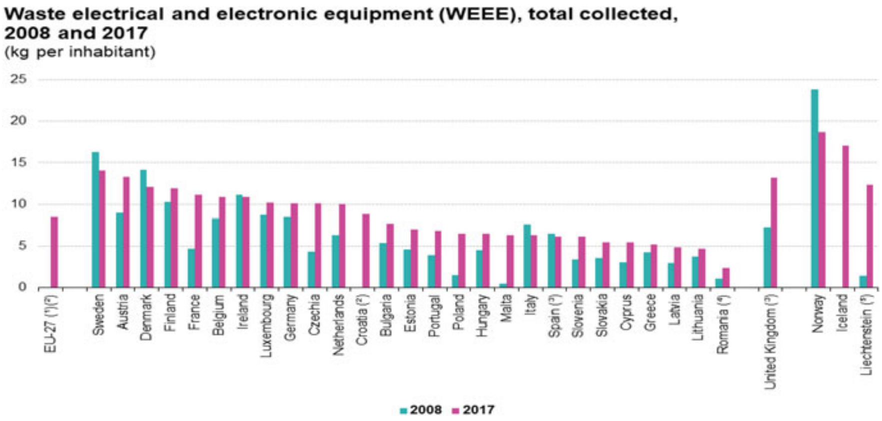

Fig. 7.16 WEEE collection rates per capita (kg/per capita) in EU 28 in 2008 and 2017. Note: Countries are ranked based on 2017 data. (1) Eurostat estimates. (2) 2008 data not available. (3) 2008 data: Eurostat estimate. (4) 2016 data instead of 2017. (5) Definition differs. (Source: EUROSTAT (online data code: env_waselee) (available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment#EEE_put_on_the_market_and_WEEE_collected_in_the_EU and https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment))

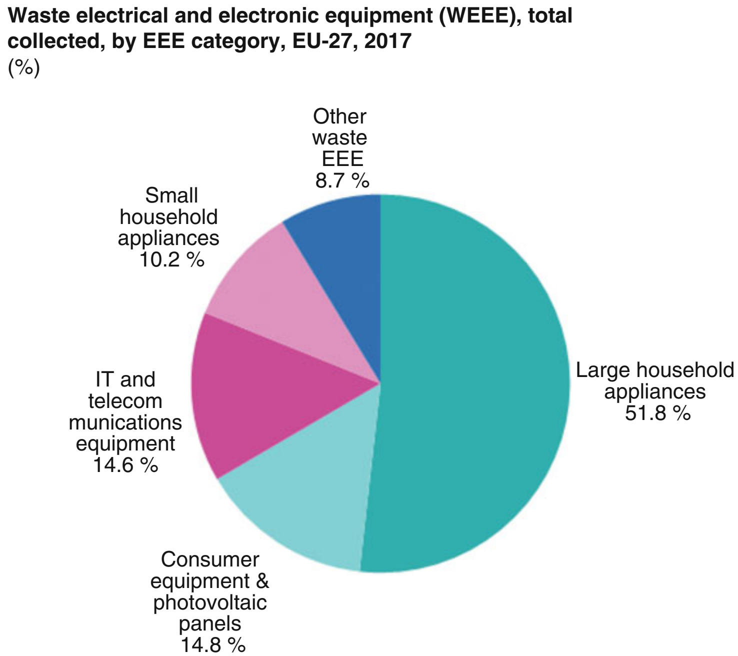

Fig. 7.17 Collected WEEE per product category in the EU (year 2017). Note: Eurostat estimates. (Source: EUROSTAT (online data code: env_waselee))

7.4.2 Collection Amount for WEEE in Italy[54]

More recent data are available for Italy compared to the EU. In the year 2020, the total collected WEEE resulted in 365.897 tonnes, whereas the amount per capita was 6.14 kg with an increase of 6.35% compared to the year 2019. The highest increase of collected WEEE resulted in the category R2 "Large household appliances" with an increase of 9.13% followed by the category R4 "Small household appliances, consumer electronics, office automation, computer appliances, lighting devices", whereas the category R5 "Light sources" recorded a decrease compared to the year 2019 (Fig. 7.18).

shows the results by WEEE category of collection rates achieved in Italy compared to the minimum EU target of 65% set by the Directive 2012/19/EU. The minimum rate of 65% of the average weight of EEE products put on the market in the previous 3 years (reference year 2019) has been achieved only by the category "R3" TV sets and displays.

7.4.3 Organization of the WEEE Management System in Italy

On the basis of the WEEE Directives and Italian Ministry Decree No. 185 of the year 2007 (Decree Law 185, 2007), the organization of the WEEE system in Italy involves the following bodies:

- The WEEE Coordination Centre (so-called CdC) that has been established by the collective systems. It optimizes and coordinates the activity of the collective

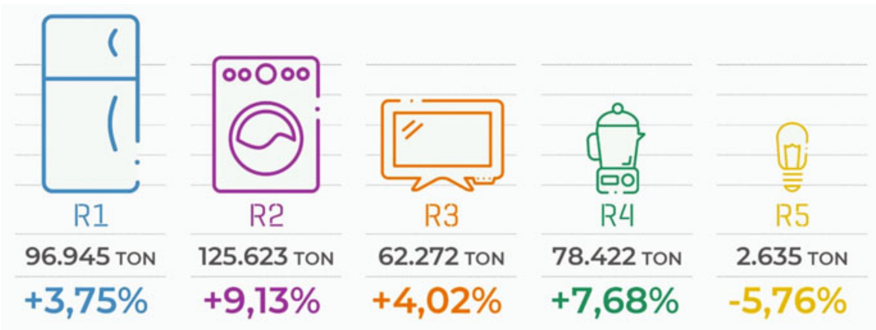

Fig. 7.18 Amount of collected WEEE by product category and percentage change compared to the year 2019 of the amount of WEEE collected. (Source: WEEE Report 2021, https://www.raeeitalia.it/it/rapporto/2021)

[54] https://www.cdcraee.it/GetPage.pub_do?id=2ca980954c369c25014ce55c67350385.

system with the purpose of guaranteeing that collective systems operate according to homogeneous practices.

- The National Register of EEE Producers that should finance the management of WEEE system. The register collects the data of the amount of EEE products put on the market. The registration is compulsory for all the producers of households EEE.
- The Supervision and Control Committee that manages the National Register of EEE Producers by calculating the market shares of the producers/collective systems. It monitors the amount of WEEE flows in relation to the target rates of WEEE separated collection and supervises on the correct application of WEEE legislation.
- The Steering Committee on the management of WEEE at the Ministry for Environment, Land and Sea Protection of Territory and Sea that has the task of supporting the Supervision and Control Committee as well as of monitoring the operativity, logistic functionality and economic efficiency of WEEE system (ANIE 2019; Remedia 2019).

At national level, 12 collective systems operate in Italy for the transport, treatment and recovery of WEEE. Every collective system manages an amount of WEEE proportional to the amount of EEE put every year on the market by the producers of the same collective system[55]. In a similar manner, some collective systems are specialized in the management of all categories of WEEE (so-called multi-supply chain collective systems) whereas others in the management of only some categories of WEEE (Remedia 2019; WEEE Coordination Centre 2018). Table 7.3 lists the 12 current Italian collective systems along with the location of their headquarters in Italy[56].

The collection of WEEE is managed and coordinated at national level by the WEEE Coordination Centre. The WEEE are collected from the different channels evidenced in Table 7.4[57]. The WEEE Coordination Centre ensures that the collected WEEE are picked up by the collective systems from the different channels. The

[55] The Decree 185/2007 evidences at the Art. 6 that the collective systems should enrol themselves in the National Register of EEE Producers before they start their operativity and communicate the data related to their establishment, the producers that join their collective system and for each producer the category of EEE according to the Decree 151/2005 (attachment 1A) as well as the types of WEEE according to the following classification: historical household WEEE, historical professional WEEE, new household WEEE and new professional WEEE. Moreover, they should communicate every year to the Supervision and Control Committee (on behalf of the EEE producers) the data related to the weight of the collected WEEE, recovered, reused and/or recycled.

[56] RAEE Italy 2019, available at https://www.raeeitalia.it/assets/uploads/rapporto-annuale-2019.pdf#:~:text=Nel%202019%20in%20Italia%20i%20Sistemi%20Collettivi%20hanno,a%20una%20raccolta%20pro%20capite%20di%205%2C68%20kg Last accessed: 11/06/2021.

[57] Recovery of waste from electrical and electronic appliances (WEEE). Available in English at https://eng.gruppohera.it/group/business_activities/business_environment/separated_collection/vegetable_oils_and_weee/page6.html. Last accessed: 12/06/2021.

Table 7.3 Collective system (consortia) operating in Italy

Collective system	Location
Apiraee	Turin
Cobat RAEE	Rome
Consorzio RLG	Turin
Ecolight	Milan
Ecoem	Pontecagnano Faiano, Salerno
Ecolamp	Milan
Ecoped	Milan
Erion	Milan
ESA Gestione RAEE	Bagno a Ripoli, Firenze
European Recycling Platform	Cassina de'Pecchi, Milan
PV CYCLE Italia	Milan
Ridomus	Milan

Table 7.4 Main channels for the collection of WEEE in Italy. (Re-adapted from data by Hera Group 2019))

Types of WEEE collection centres	Description
Waste collection centres (drop-off points)	These are set up and managed by municipalities and companies authorized to handle WEEE. Collection centres are open to citizens that can dispose of household WEEE free of charge. Collection centres can also collect WEEE from one or more municipalities and accept WEEE from distributors, installers and repair centres
Consolidation centres	These sites apply for WEEE the schemes "One against One" and "One against Zero". They are served directly by the consortia and can be set up at the point of sale of a distributor or at another place
Large users	These are sites registered by public or private organizations (airports, companies, hospitals, barracks, etc.) that produce significant amounts of WEEE in the lighting category (R4 and R5) and can therefore be served by a pick-up service provided by the consortia
Private collection centres	These centres are mainly set up by the consortia to store WEEE from voluntary collection activities and mainly for lamps
Installers	These centres are directly served by the consortia and managed by light source installers (R5), where WEEE from private households is stored after installing a new equipment
Repair centres and points of sale	In retail points of sale and repair centres, WEEE from private households are collected free of charge against the sale of equivalent household appliances ("One against One")
Treatment plants	These regard the companies that provide storage (to a large extent) and/or processing for recovery, recycling or waste to energy

collective systems are in charge of their subsequent transferring to the treatment and recovery plants authorized by the Coordination Centre[58].

After the collection, the WEEE are transported to the first treatment plants where they are dismantled in order to safely remove the hazardous components and to separate the valuable materials that can be recovered (Biganzoli et al. 2015). Then, separated components are transported from the first treatment plants to recovery plants (material or energy recovery) or disposal plants (Ecorit 2017). On 2016, 940 treatment plants were operative in Italy. Most of the plants were located in Northern Italy (665 plants) whereas in a lower extent in the centre (148 plants) and in the south and the islands (127 plants). Only a few of these plants perform the treatment for the recovery and recycling of the WEEE as most of them store temporarily the WEEE (WEEE Coordination Centre 2016).

7.4.4 Beyond Recycling: Case Studies from Italy

The Atlas of the CE shows the following case studies of individual organizations whose activities involve the repair, reuse or remanufacturing of WEEE. The organizations and their CE policies can be classified in the following:

1. Web platform connecting sellers and consumers of unsold EEE products:
   (a) **BEPRO: website for the purchase and sale of surplus original cartridges and spare parts for printers.** The web platform has been created in the year 2015 by a company active in the remarketing of consumables and spare parts for original printers, copiers and faxes. It allows consumers and companies to sell toner, cartridges and other original equipment for printers that have been purchased previously by them and never been used before. Such products are then put on the sales site where users of such products can purchase toner and cartridges for their printing devices at an advantageous price. This provides both economic benefits for them and environmental benefits for the society coming from the landfilling avoidance[59].
2. Repair of WEEE products (hardware, software):
   (a) **E-Repair: repair and regeneration of industrial electronic boards**. The company (active since more than a decade) has implemented a collection and repair system for obsolete electronic boards, which are disposed of by manufacturing companies. The extension of the life of industrial electronic boards (in some cases are more than 30 years old) regenerates still functional products reducing the number of electronic boards to be disposed of. The

[58] Recovery of waste from electrical and electronic appliances (WEEE). Available in English at https://eng.gruppohera.it/group_eng/sustainability/thematic-reports/tracking-waste/vegetable-oils-and-weee/recovery-of-waste. Last accessed: 12/06/2021.

[59] BEPRO, available at https://economiacircolare.com/atlante/bepro-italia/. Last accessed: 03/06/2021.

company adopts a specific process of regeneration that entails the reduction of the amount of water, the use of detergents with a lower environmental impact and the use of renewable energy self-produced by means of PV panels placed on the roof of the factory. Finally, in order to avoid the consumption of space and energy use, the company uses a system of automatic vertical warehouses allowing the optimization of the available space[60].

(b) **Binario Etico: repair of personal computer and use of recovered and regenerated hardware**. This is a benefit corporation founded in 2006 that is involved in the provision of hardware products and services and recovery of hardware products. The latter are collected and then recovered in the plants of the company whenever is possible or are correctly disposed of if they cannot be recovered. The company works with local suppliers who share the same mission with regard to the use of software (that should be non-proprietary software) as well as other social criteria. Finally, the employees are also involved in the mission of the company and adopt more sustainable and circular behaviours such as the use of public transport or bicycles to go to the work[61].

(c) **Reware**: **recovery and regeneration of IT equipment discarded by companies**. The cooperative company (social company) has a decade of experience in the repair and regeneration of personal computers disposed of by the companies. The computers undergo disassembling in the plants of the company, the components are tested, and the data are deleted in a safe and certified way. The remanufactured computers are then sold again as they can be used for many years, thanks to the regeneration of various devices, both hardware (increase of ram, change processors, use of SSD disks) and software (use of GNU/Linux distributions in particular). With regard to the results of the company's activities, since 2015, it has regenerated about 1500 computers or about 6 tonnes of IT equipment. Moreover, it estimates of having doubled the useful life from an average of 4 years to an average of 8 years. This contributed to avoid relevant environmental impacts since remanufactured computers avoid the purchase of an equivalent new computer. The company is also involved in several projects such as those in collaboration with non-profit organizations (such as Legambiente) aimed at increasing the awareness of environmental sustainability of the sector or related to the training of professionals in the electronics sector as well as to cooperation projects in Africa[62].

(d) **Hacking Labs: regeneration of WEEE and recovery of broken or dismantled PC, tablet, TV and smartphones**. This is an association of social

[60] E-Repair, available at https://economiacircolare.com/atlante/e-repair/. Last accessed: 03/06/2021.

[61] Binario Etico, available at https://economiacircolare.com/atlante/binario-etico/. Last accessed: 03/06/2021.

[62] Reware, available at https://economiacircolare.com/atlante/reware/#field-group-tab-4. Last accessed: 03/06/2021.

promotion with a laboratory that repairs electronic products (personal computers, desktops and notebooks, servers, smartphones and tablets) in both the software and hardware. The electronic products and components that cannot be reused are dismantled to recover raw materials such as iron, copper and aluminium or are sent out for creative reuse such as the production of key rings made with chips or alarm clocks and electronic cards. The association also aims to disseminate knowledge about the electronics and IT sector in particular cases where the economic conditions prevent the purchase of a personal computer or the attendance of courses. It promotes the culture of reuse, repair and regeneration of personal computers and their subsequent donation to schools, parishes and other associations[63].

(e) **Astelav: regeneration and redistribution of household appliances**. The company has a long history in the repair of households' appliances and distribution of accessories and spare parts for household appliances. Astelav started dealing with the circular economy since 2016 with the launch of Ri-Generation project aimed to the regeneration of WEEE and in particular washing machines, dishwashers, kitchens and refrigerators. Through Ri-Generation, the WEEE products, instead of being sent to costly disposal, are put back into a new production cycle and resold at advantageous prices (−50% of the original price). The remanufactured appliances can be purchased at three points of sale in Turin, by associated retailers throughout Italy or through the e-commerce service. It is also important to mention the social responsibility of the company that promotes the correct treatment of WEEE by collecting them by the citizens of the city of Turin who can donate their WEEE. Moreover, in the Ri-Generation project, people in particular conditions such as the immigrants are employed and trained[64].

(f) **RIMAFLOW: repair and recycling laboratories and production and distribution of agricultural products**. The laboratory has been created by the former employees of a factory that closed their activities after a crisis. RIMAFLOW has many laboratories including one dealing with the recovery of WEEE. These come from companies or private individuals and after the repair are donated or sold at low prices to schools, institutions and less well-off individuals[65].

3. Remanufacturing of electronic products and components:

(a) **SAPI: production of remanufactured cartridges and refurbished printers**[66]. The company is active since the year 1993 and specialized in

[63] Hacking Labs, available at https://economiacircolare.com/atlante/hacking-labs/. Last accessed: 03/06/2021.

[64] Astelav, available at https://economiacircolare.com/atlante/astelav/. Last accessed: 03/06/2021.

[65] RIMAFLOW, available at http://economiacircolare.com/staging/atlante/rimaflow/#field-group-tab-2. Last accessed: 06/06/2021.

[66] SAPI, available at https://economiacircolare.com/atlante/sapi/#field-group-tab-2. Last accessed: 03/06/2021.

the remanufacturing of printers, multifunction and copier (toner, used original cartridges, drums and spare parts) and related hardware (printers and photocopiers). In the 2 factories of the company, up to 50,000 cartridges per month are remanufactured in a high-quality manner (the quality of the remanufactured cartridges is the same as the original cartridges) and sold again at more affordable prices. The environmental and economic benefits of the regeneration of such products are very relevant as, e.g. in Italy, every year about 30 million inkjet cartridges and 10 million toner cartridges end up in landfills or are burned. Such benefits have been certified by an LCA study whose results evidenced that remanufactured cartridges avoid environmental impacts compared to original cartridges (−83.99%).[67]

4. Promotion of the reuse of regenerated electronic products:
   (a) **Green Idea Technologies: start-up company for certified environmental consulting services in the personal computer sector.** The start-up is active since 2014 in the cities of Sanremo and Bologna located, respectively, in Liguria and Emilia-Romagna regions (Northern Italy). It is the first European company dealing with “Certified environmental consultancy in the IT sector”. Its activity consists in helping its customers to reduce CO_2 emissions by providing innovative solutions for the purchasing and recycling of electronic products. In that, the start-up supports the customers in the purchase stage as well as at the end of life by allowing for the reuse processes (reconditioning) of electronic products avoiding the production of new waste and increasing its service life. The company also certifies the saving in terms of CO_2 derived from the reconditioning of the personal computers. In 2017, the company has received by the European Institute of Innovation and Technology the “Climate-KIC Accelerator” award as the best Italian company involved in the improvement of climatic conditions[68]. Finally, the company is certified as a benefit corporation since 2017.
5. Academic research in the electric and electronic product value chain:
   (a) **RISE (Research & Innovation for Smart Enterprises): modelling the impacts of the implementation of circular economy in companies.** The research laboratory of the Department of Mechanical and Industrial Engineering (University of Brescia) contributes to the development of innovation (including the orientation to circular economy innovation) of processes and products and of business models supporting companies to become more competitive and circular. In this early stage of the transition, the development of methods and frameworks that show the multiple benefits of CE scenarios is

[67] More details about the results are available at the following website of the company: https://www.sapionline.it/en/regenerate-a-benefit-for-all. Last accessed: 01/06/2021

[68] Green Idea Technologies, available at https://economiacircolare.com/atlante/green-idea-technologies/. Last accessed: 03/06/2021.

very useful in favouring companies' decision of implementing circular practices[69].

7.5 Food Value Chain

The production of food is noteworthy known to generate relevant impacts to the environment. About one-third of global GHG emissions come from the food sector and in particular from the intensification of farming activities including intensive livestock farming. These are also the cause of negative effects on the biodiversity of natural ecosystems and on human health[70]. Additionally, a relevant issue in food value chain regards the loss or waste of food. In overall, for example, the latter is estimated about 17% of the total food available to consumers in 2019 according to a recent research by the United Nations[71]. In order to further address the issue, the EC evidenced in the EU CE Action Plan that it would have proposed a target on food waste reduction in the EU Farm-to-Fork Strategy. The latter has been adopted last year with the aim of promoting and supporting a more fair, healthy and environmentally friendly food system[72]. In that, it proposes by 2030 to reduce in agriculture the use of pesticides (including more hazardous pesticides) by 50%, the excess of nutrients, as well as supports the development of organic agriculture. Moreover, the strategy aims to sustain healthy diets, develop a sustainable food labelling framework to empower consumers in their choices of sustainable and healthy diets and fight food waste by proposing legally binding targets that can reduce food waste generation in the EU[73].

The transition to CE will contribute to further strengthen the EU Farm-to-Fork Strategy (Fig. 7.19) given its focus on cleaner and sustainable production processes and natural resources' efficiency, waste avoidance and minimization by design, renewable energy transition and better conservation of finite resources. In that, it will favour the achievement of EU Farm-to-Fork Strategy goals in the whole food

[69] RISE, available at https://economiacircolare.com/atlante/laboratorio-rise/#field-group-tab-4. Last accessed: 03/06/2021.

[70] European Commission, Farm to Fork Strategy, available at https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en#:~:text=The%20Farm%20to%20Fork%20Strategy%20is%20at%20the,the%20COVID-19%20pandemic%20if%20they%20are%20not%20sustainable. Last accessed: 03/06/2021.

[71] https://www.unep.org/news-and-stories/press-release/un-17-all-food-available-consumer-levels-wasted.

[72] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381.

[73] European Commission, From Farm to Fork: our food, our health, our planet, our future. The European Green Deal, available at https://ec.europa.eu/commission/presscorner/detail/en/fs_20_908. Last accessed: 03/06/2021.

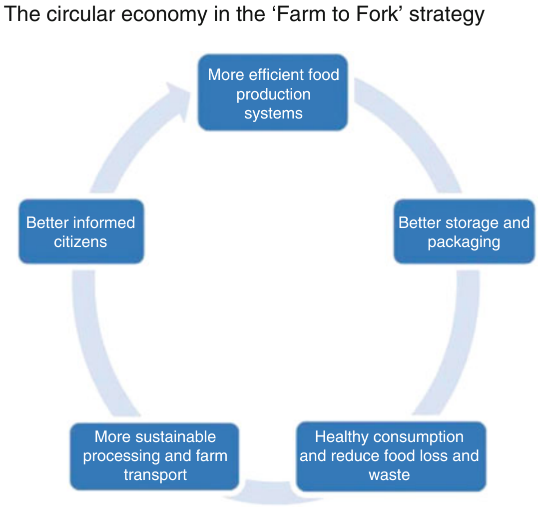

Fig. 7.19 Circular economy contribution to Farm-to-Fork Strategy in the whole food value chain. (Source: European Commission 2020)

value chain by improving some hotspots such as packaging, storage, transport, food waste and imported food[74].

7.5.1 Generation and Recovery Opportunities for Food Waste in the EU

Food waste is defined in the framework of the EU FUSION project (2014) as "food and inedible parts of food removed from the food supply chain" that is to be disposed of (e.g. crops ploughed back into the soil, left unharvested or incinerated, food disposed of in sewers or landfill sites or fish discarded at sea) or used for nutrient recovery or energy generation (e.g. through composting or anaerobic digestion and other bioenergy pathways). The definition of food waste widens the concept of biowaste since it includes the food and inedible parts removed from the food supply chain and points out the need for its disposal or the opportunities for its resource or energy recovery. At this regard, as we evidenced in Sect. 7.2.2, the EU monitoring indicators framework for the CE includes a specific indicator named "recycling rate of biowaste". A further distinction appears between the concept of food losses and food waste. The first term refers to the stages before consumption and arises from inefficiencies in food production and processing, whereas food waste is due to factors in the consumption stage (e.g. food not eaten because of purchase of an excessive amount than what is needed, it reached the expiry date, of inappropriate

[74] European Parliament, From Farm to Fork strategy on sustainable food, available at https://www.europarl.europa.eu/RegData/etudes/ATAG/2020/646132/EPRS_ATA(2020)646132_EN.pdf. Last accessed: 03/06/2021.

packaging, of low consumer appeal and so on) (European Commission's Knowledge Centre for Bioeconomy 2020). Finally, food wastage comprises both food loss and waste since it includes any food lost by deterioration or waste. In the EU, the amount of food waste has been calculated to be about 20% of the total food produced in the year 2011 (European Commission's Knowledge Centre for Bioeconomy 2020). There are uncertainties in the estimates of the annual amount of food waste due to the different approaches used in the studies. For example, Caldeira et al. (2019) calculated an annual amount of 129 Mt. of food waste, while the FUSION project calculated about 88 Mt. of food waste.[75] In the EU food supply chain, most of the share of total food waste is generated in the consumption stage (46%). Then follow the other stages, production with a share of 25% and processing and manufacturing (24%), while the distribution and retail stage has the lowest share (5%). shows that in the agricultural stage or primary production, the categories "fruit" and "vegetables" account for the most significant food losses (76% of the total), while in the consumption stages, they are wasted less compared to other food categories (42%).

Food losses and waste in the supply chain can be valorized in different options (Santagata et al. 2021; European Commission's Knowledge Centre for Bioeconomy 2020). At present, for example, waste that cannot be consumed by humans can undergo different types of valorization routes whose economic value ranges from low to high value. The latter regard, for example, the extraction and recovery of value-added components for industrial applications (e.g. cosmetics and nutraceuticals, food preservation and packaging products, pharmaceuticals, etc.), as well as to the conversion of food waste into bio-based building blocks that can be used in a wide range of applications as biomaterials (e.g. bioceramics, biopolymers, etc.) (Santagata et al. 2021; European Commission's Knowledge Centre for Bioeconomy 2020). There are environmental, social and economic benefits associated with the recovery of food waste and in particular those related to the avoidance of disposal in landfills and avoided extraction of natural resources (Ghisellini et al. 2023; Santagata et al. 2021). Many challenges (economic, technological, environmental) still exist in the recovery, while the opportunities of food waste recovery should be properly evaluated taking into account the whole life cycle of by-products by means of standardized methods e.g. life cycle assessment (Camana et al. 2021; Mirabella et al. 2014). The latter is widely used in evaluating the application of circularity in the agri-food sector (Ncube et al. 2021; Stillitano et al. 2021; Pollaro et al. 2020) both as a single method or in combination with other methods (Camana et al. 2021) such as Emergy Accounting (Santagata et al. 2021). In this latter case, with LCA and Emergy Accounting, it is possible to widen the range of the environmental categories and scale of analysis (both temporal and spatial)

[75] For example, Caldeira et al. (2019) adopt a mass balance approach that combines different sources of information with the breakdown into the major EU food groups. FUSIONS uses normalization factors (based on, e.g. food produced, population and turnover) from a limited number of countries and upscales the data to the EU level (From European Commission's Knowledge Centre for Bioeconomy 2020).

increasing further the understanding of the proposed valorization routes for food waste (Santagata et al. 2021).

7.5.2 Generation of Food Waste in Italy

The Last-Minute Market/Waste Watcher Observatory evidences that in the year 2020, food waste generation in the Italian households for the first time recorded a decline of about 25%. The results of the survey also revealed that 66% of Italians believe that there is a strict connection between food waste and environmental and human health. For one Italian out of three, aspects related to the impact on human health are relevant in the purchasing decisions of buying food. Moreover, 40% of the respondents declared to be aware of the needs of protecting the environment even without the influence of movements like the "Fridays for future". Instead, 33% of respondents evidenced to be influenced by the awareness of this movement that has contributed to increase their attention to sustainability in everyday life (16%) or at least to start reflecting on such issues (17%)[76].

With regard to the data about food waste, in the year 2020, the amount per capita was about 27 kg (529 g in a week). Compared to the year 2019, the reduction of food waste has been equal to 11.78% (or 3.6 kg). This means that in the year 2020, over 222,000 tonnes of food have been saved from being wasted in Italy totalling a saving of €6 per capita or €376 million at national level. The value of national domestic food waste reaches €6 billion and 403 million that ends up to €10 billion if considering the losses in the food value chain from agricultural stage to distribution which amount is €3,284,280,114. By weight, this means that in 2020, 1,661,107 tonnes of food at home were wasted in Italy and 3,624,973 tonnes if losses and wastes of the supply chain are included (data Waste Watcher International/DISTAL University of Bologna for Waste campaign Zero and Ipsos surveys)[77].

7.5.3 Food Sustainability in the Whole Life Cycle: Case Studies from Italy

The Atlas of the CE includes the circular practices of organizations that aim to make more sustainable the production of food at the farming stage as well as in other stages of the life cycle including the reduction of food losses and waste after the consumption stage. We have grouped the organization as follows:

[76] Waste Watcher International Observatory, available at https://www.sprecozero.it/waste-watcher/. Last accessed: 03/06/2021.

[77] https://www.foodaffairs.it/2021/02/03/sostenibilita-spreco-di-cibo-cause-e-strategie-di-prevenzione-lo-studio-spreco-il-caso-italia-di-waste-watcher-international-observatory/.

1. Non-profit organizations operating in food recovery and redistribution:
   (a) **Avanzi Popolo 2.0**: **contrast to food waste, food sharing, recovery of food surplus and awareness**. The association recovers food surpluses for social and ecological purposes. Its activity of recovery and redistribution of food surpluses' activity is based on the creation of a network of stable relationships with a high number of third sector subjects located as close as possible to the place where the surplus occurs, in order to minimize the distance and the impacts for both food and the environment as well as valorize the contribution of partners who are involved in the food redistribution of their specific area.
   (b) **Equoevento: recovery and redistribution of food surplus from parties and other events.** Their activity deals with the recovery of food surplus from weddings, conferences and sports events and its redistribution to charitable canteens. In this way, by avoiding food to become waste, all the resources and ingredients used for the preparation of the food are optimized. Furthermore, the surplus bread is delivered to a craft brewery where people (in external criminal execution), coming from the Roman prison of Rebibbia, are trained and inserted in the craft beer supply chain. In the year 2020, the organization launched a project against food waste in supermarkets and food shops named YouFeed where shops can register on the platform and offer boxes, with surplus fresh products or those close to expiry, and donate to families who need them and can collect from the shops closest to their home[78].
   (c) **Banco Alimentare: recovery of food surpluses from large events and redistribution to charities and canteen for poor people.** The activity of the organization consists in recovering food that is still edible but no longer marketed and redistributing it to associations that help poor people in Italy. The organization has been founded in 1989 and currently has a network of 21 associated organizations in Italy. In 2016, it recovered about 70,000 tonnes of food and redistributed it to about 8000 associations that help a half million of poor people. It operates through 1700 volunteers and 120 employees[79].
   (d) **RECUP: against food waste and social exclusion, a project of active citizenship.** The project born in 2014 from the idea of a group of academic students (girls) aimed to disseminate the importance of citizens' actions against food waste and its valorization as well as contrast social exclusion. From 2016, the group operates in an association of social promotion that currently is active in local markets of the city of Milan. The food is recovered and delivered at the closure of the markets on the same packaging of the

[78] Equoevento, available at https://economiacircolare.com/atlante/equoevento/#field-group-tab-2. Last accessed: 02/06/2021.

[79] Banco Alimentare, available at https://economiacircolare.com/atlante/banco-alimentare/. Last accessed: 02/06/2021.

shops and delivered with trolley and cargo bikes. The food is not delivered in plastic bags as people are invited to take the recovered food with reusable bags[80].

(e) **Io Potentino**: **recovery of food and redistribution of food surpluses**. The association is operative in the city of Potenza (Southern Italy). Since 2014, it has created a system for managing food surpluses from commercial activities and/or public and private events and its redistribution to people in need throughout the city at the end of the harvest. The entire donation, collection and distribution process is carried out with maximum transparency, thanks to a software that guarantees the traceability of donations. So far, the association has collected and redistributed 11,302.77 kg of food.[81]

(f) **Disco Soupe: public events of circular cooking for recovering unsold food**. The main goal of the organization is increasing the awareness of people on the problem of food waste and the need for alternative solutions to the problems of waste and climate change by proposing participative solutions. Disco Soupe recovers perfectly edible foods that would be discarded and gives them a second life by cooking it through public awareness events. The collected food mainly consists of fruit, vegetables and bread products (thrown away for various reasons such as aesthetic factors as in the case of products from local farms or unsold at the end of the day or week from local markets). Everything is recovered at "zero km" in order to minimize the transport of goods and, at the same time, increase the awareness of local traders and the importance of new practices in the area. The project involves the local community, which is encouraged to minimize excessive waste and reach the event in the most sustainable way[82].

(g) **Eco dalle Città**: **promotion of good practices for the management of food and recovery of surplus food from local markets.** The association is involved in many projects that are aimed to revalorize food and other goods such as books and save them from being incinerated. With regard to food, the members and volunteers of the Eco dalle Città association every day, from Monday to Saturday, recover unsold food from the street vendors of the Porta Palazzo market (Turin) and then redistribute it for free to a group of people in need. It is interesting to point out that before the recovery, volunteers and members distribute bio-compostable bags to street vendors to promote separate collection within the market. After the recovery and distribution of the bags, the members of the association help in collecting the empty boxes and organic waste[83].

[80] RECUP, available at https://economiacircolare.com/atlante/recup/. Last accessed: 02/06/2021.

[81] Io Potentino, available at https://economiacircolare.com/atlante/io-potentino/#field-group-tab-4. Last accessed: 02/06/2021.

[82] Disco Soupe, available at https://economiacircolare.com/atlante/disco-soupe-firenze/#field-group-tab-2. Last accessed: 02/06/2021.

[83] Eco dalle Città, available at https://economiacircolare.com/atlante/eco-dalle-citta/#field-group-tab-2. Last accessed: 02/06/2021.

(h) **Foodbusters: recovery of surplus food and increasing awareness against food waste.** The association is located in the Marche region (Central Italy). Surplus food that is recovered during parties, meetings and weddings is delivered to social canteen closest to the place of the event, preventing the production of waste and supporting those who offer a social assistance service. The donation of the surplus food coming from public events makes the latter fairer and more sustainable and conveys particular ethical values for the participants[84].

2. Sustainable and circular agro-food production chain:
   (a) **De Matteis Agroalimentare: pasta made with durum wheat 100% Italian from short supply chain**. The company produces the pasta "Armando" that is made with 100% Italian durum wheat from the supply chain that the company created in 2010 with over 1400 companies located in Central and Southern Italy. The wheat coming from such companies is worked directly in the mill included in the pasta factory and transformed into semolina that is used for the production of the pasta. The latter is distributed in FSC-certified packaging that can be recycled as paper in separate collection. This eliminates plastic in packaging, thanks to more innovative materials[85].
   (b) **Noi Genitori Factory: social cookie, energy efficiency and waste reduction**. It is a social company that produces dry bakery products with a high social, economic and environmental value. The biscuit factory uses renewable energy and raw materials from the local supply chain (e.g. the butter from the Latteria Sociale Valtellina and the organic honey from a local producer) and employs people with disabilities who enhance with this work their skills and improve their well-being[86].
   (c) **Life DOP Virgilio Model: circular model for the Parmigiano Reggiano and Grana Padano chain**. This is a project funded by the European Union as part of the 2015 Life Program and involves the Parmigiano Reggiano and Grana Padano supply chain in the creation of a circular economy model with lower environmental impact. The Life DOP project involves partners throughout the Grana Padano and Parmigiano Reggiano production chain: Consorzio Latterie Virgilio, Associazione Mantovana Allevatori, Consorzio Gourm.it, San Lorenzo Agricultural Cooperative, Northeast Agricultural Consortium and University of Milan. The goals of the project imply among others the definition of an environmentally sustainable production model for Parmigiano Reggiano and Grana Padano in the Province of Mantua, the promotion in the entire production chain of an efficient and circular use of

[84] Foodbusters, available at https://economiacircolare.com/atlante/foodbusters/#field-group-tab-2. Last accessed: 02/06/2021.

[85] De Matteis Agroalimentare, available at https://economiacircolare.com/atlante/de-matteis-agroalimentare-pasta-grano-italiano-filiera-corta/#field-group-tab-2. Last accessed: 03/06/2021.

[86] Noi Genitori Factory, available at https://economiacircolare.com/atlante/noi-genitori-factory/#field-group-tab-2. Last accessed: 03/06/2021.

resources, the evaluation of innovative good practices suitable for the territory and the dairy cattle chain. Moreover, the project adopts LCA method based on primary data collected at all stages of the supply chain aimed to develop a sustainable model and its replicability[87].

(d) **Filab dairy circular company producing Mozzarella di Bufala Campana DOP**. The Mozzarella is made only with fresh milk and Ricotta di Bufala Campana DOP (buffalo ricotta cheese) with the whey coming from the production of mozzarella cheese. The additional by-products of buffalo milk are destined for pastry shops/butter factories and to other the local farms. The primary packaging is recyclable, while the secondary packaging is currently at a research stage to make it recyclable. The company is launching policies to reduce the purchase of energy from fossil sources. Moreover, it promotes employee awareness towards the reduction of wastewater in the processing phases as well as reduction of emissions related to the transport of its products by choosing transport with contractors who carry out groupage. The choice of the company's suppliers (for both typical and ordinary purchases) is made on the basis of their involvement in environmental and social certifications and/or qualifications[88].

(e) **Fermenti Sociali: production of beer with self-produced crops and machines**. The company is an authorized microbrewery where 100% of the cereals to make the beers are self-produced, cultivated and transformed in the company. Most of the equipment used for malting and making the beer is recovered and adapted for these purposes. The production process generates as by-products heat that is partially recovered, while the wastewater ends up in the phytodepuration plant of the company. The beer is distributed in local markets and local restaurants in reusable packaging[89].

(f) **Serrocroce: brewery and farm, recovery of by-products of barley cultivation.** The barley, hops and spices used as raw materials to produce the beer are self-produced. The latter is the first beer from an agricultural and zero-km supply chain in the Campania region. The CE policies of the company entail the recovery of materials and the valorization of raw materials and of by-products. The beer threshers, which are the by-product coming from the hot extraction of germinated barley, are reused for the production of taralli (a type of salted biscuit) and bread that are the typical products offered during tastings in the brewery. The remaining by-product, rich in fibre and sugars, is used by local livestock farms as food for the animals. The company also

[87] Life DOP Virgilio Model, available at https://economiacircolare.com/atlante/life-dop-modello-virgilio/. Last accessed: 03/06/2021.

[88] Filab, available at https://economiacircolare.com/atlante/filab/#field-group-tab-2. Last accessed: 03/06/2021.

[89] Fermenti Sociali, available at https://economiacircolare.com/atlante/fermenti-sociali/#field-group-tab-2. Last accessed: https://economiacircolare.com/atlante/fermenti-sociali/#field-group-tab-2 .

recovers the cleanest fraction of the water used for washing the plants as well as the rainwater. These are then reused for field irrigation.[90]

7.6 Concluding Remarks

The aim of the present study was to provide an overview of the current transition to CE in both the EU and Italy in some key product value chains (electronics and ICT, packaging, plastics and food) considered as relevant for their environmental impacts and circularity potential in the EU Action Plan of the CE. In order to achieve our goals, the present study summarized some of the key elements of the EU Action Plan of the CE and its role in the EU environmental political agenda as well as the CE indicator framework. A brief background on the transition to CE in Italy at different scales (micro, meso and macro) is also provided highlighting some of the main institutional initiatives and documents such as the strategic position document that defines the Italian strategy for the CE.

Then, we evaluated for the EU and Italy the annual flows of municipal solid waste (MSW) generated and recycled, the total waste and their composition, the amount of packaging waste generated and recycled per capita as well as the recycling rates for plastic packaging waste and e-waste. Moreover, some data about food waste losses and waste in EU and Italy have been discussed.

In the EU 27 countries, the EUROSTAT data related to MSW evidence a reduction in the year 2019 compared to 2005 of the amount of the generated MSW, while the recycling rates increased from 32% (year 2005) to 48% (year 2019). Instead, the amount of total waste generated evidences an increase in 2019 compared to the year 2004 for both the EU 27 countries (+3.9%) and Italy (+23.4%). The recycling rates of the different waste streams (packaging waste, plastic packaging waste and e-waste) for the EU 27 countries and Italy show an increase in the investigated periods.

For each of the selected waste stream (plastic packaging, electronics and ICT and food), we also evaluated the CE practices of 32 companies that are available on the Italian Atlas of the CE. The 32 case studies show alternative CE practices (reduction, material substitution, repair, reuse, remanufacturing) to the recycling for the prevention/management of the different waste streams and in overall a different system for the management of the waste streams compared to the recycling option.

The cases of packaging show the availability of alternative materials to plastic packaging that have a lower environmental impact (paper and biomaterials) as well as that the impacts of alternative packaging materials (e.g. "Greenpaper") and packaging products (e.g. "GreenboxX") are evaluated and certified by product certifications such as "EPD". The valorization of packaging waste materials

[90] Serrocroce, available at: https://economiacircolare.com/atlante/serrocroce/#field-group-tab-2. Last accessed: 03/06/2021.

previously disposed of in landfills contributes to generate new secondary materials ("EcoAllene") totally recyclable whose quality and origin are certified by "Remade in Italy" in class A^+, a label that is given in the case of materials with a recycled content higher than 90% compared to the total. Moreover, at both industrial and consumer level, the product design aimed to the reuse at the end of life of a packaging contributes to reduce the environmental impacts of materials such as plastics by increasing its lifetime. For other materials, the creative reuse (e.g. wood) of packaging can be designed. Moreover, the shops that sell bulk products reduce the amount of packaging waste and increase the awareness of the importance of waste reduction and packaging minimization and reuse.

The cases of treatment of WEEE (personal computer and other related hardware, household appliances), beyond recycling, show the several companies involved in applying the different options (repair, reuse or remanufacturing) for the valorization of WEEE products and their reintroduction in the production and/or consumption cycles. By means of such options, the lifetime of electrical and electronic equipment (EEE) and their components can be expanded. The e-repair companies also contribute to overcome the negative perception of consumers towards such products by sharing and disseminating the knowledge on them including the importance of their correct management. Given the lower price of remanufactured EEE compared to new products, they can also be purchased by people who cannot afford a new EEE. Finally, with regard to the food supply chain, the analysed associations by recovering and redistributing surplus food (coming from events or local markets or other context) or still edible food (not marketable) make concrete actions towards food waste avoidance and its further valorization as well as contrast social exclusion and poverty. Moreover, they also favour the diffusion of less impactful mobility lifestyles by promoting the recovery of food by bikes or minimizing the transport distance through an adequate planning and by means of the use of digital technologies and web platforms. In the agro-food supply chain, the creation of collaborations between companies and their suppliers as well as with other stakeholders contributes to develop many sustainability-oriented practices and activities, namely, to improve the traceability of products, the promotion across the supply chain of an efficient and circular use of resources, the evaluation of innovative good practices suitable for the specific territory and the different food product chain (crops, dairy, beverage) and the adoption of renewable energies and more sustainable recyclable packaging made of recycled inputs.

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Status of the Adoption and Practice of Circular Economy in Mexico

8

Gabriela Munoz-Melendez

Abstract

In Mexico, the adoption and practice of circular economy (CE) are recent but growing rapidly. Initiatives driven by international aid and governmental support alike are in their early stages but firmly on their way to become realities. In this document, the implementation of CE measures in Mexican sectors is reviewed; to do so, two methods were applied: the first was a bibliometric analysis carried out on thematic documents in both Spanish and English, while the second method consisted in reviewing web pages' content of corporations claiming to apply CE actions in their operations. The analyses were complemented by two brief reviews: the first on national regulations and the second on public perception. Findings indicated that CE thinking has been implemented mainly in the large corporations and in the waste management sector; CE implementation is being supported by the government at national and subnational levels. A pending task is to include Mexican consumers in the CE transition given that that there is a low level of public understanding regarding the CE meaning, but consumers are willing to recycle plastics; thus, there is a need of continuing education and access to programs and recycling facilities for Mexican consumers to help CE implementation in the country. In the region, Mexico shows comparative advantages regarding CE implementation in the waste management sector and adoption on the industry operated by large corporations, but CE adoption on the mining and extractives sectors has not been addressed.

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Keywords

Waste · Circular economy · Mexico

8.1 Introduction

Although the concept of "circular economy" dates back to 1966 (Boulding 1966), so far, there is no unique and universally accepted definition, yet this has not represented an obstacle for the idea to be widely disseminated and adopted around the world. Latin America and the Caribbean (LAC) has not been an exception; by 2019, it was reported that more than 80 public initiatives related to CE have been launched (Cerna-Martinez et al. 2019). In the LAC region, the CE model is recognized as a mean to achieve sustainable development, but for a successful transition, it is conceded that the CE strategies must be adopted in the industry, in particular the mining and extractives sector, waste management and recycling, and the bioeconomy (Schroder et al. 2020), all this under a "just transition" approach, in the sense that preexisting unequal social and economic conditions do not perpetuate under the CE model (Schroder 2020).

To accelerate the CE transition in LAC, among many initiatives, the United Nations Framework Convention on Climate Change (UNFCCC) through the Climate Technology Centre and Network (CTCN) is promoting and developing national, sectoral, or process-specific circular models in 11 countries to tackle climate change. CTCN provided technical assistance in CE in two phases: the first was launched in 2019 and included Chile, Brazil, Mexico, and Uruguay, and the second started in 2020 and incorporated Ecuador, the Dominican Republic, Cuba, El Salvador, and Paraguay. This initiative sought to identify potential CE projects in geographical areas and set appropriate country road maps to implement CE activities (Salinas and Rodriguez 2020).

In Mexico, the CE adoption and practices are recent but growing rapidly and have been assisted by foreigner initiatives further than the CTCN, as demonstrated by the Finnish-Latin American Trade Association Seminar in 2017, the second "Meeting on Circular Economy" held on 2018 with the support of the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ), and the "Forum on Conservation Economics and the Transit to a Circular Economy" celebrated in 2018 with Canadian aid. In addition to the international cooperation, non-governmental organizations have worked together or separately to promote CE in the country.

Furthermore, the Mexican government is also contributing by not only issuing regulations on the topic—strictly speaking—but setting the legal basis to transit toward a CE model; the evolution of legislation to incorporate the CE application in Mexico is shown in Fig. 8.1. It must be added that governmental actions are additional to the commitments taken in the Environmental Conventions and United Nations' Protocols that Mexico has signed; of these, two are the most relevant to foster CE implementation: (1) the Agenda 2030 and Sustainable Development Goals (SDG), specifically 3, 6, 7, 11, 12, and 13, and (2) the Paris Agreement goals.

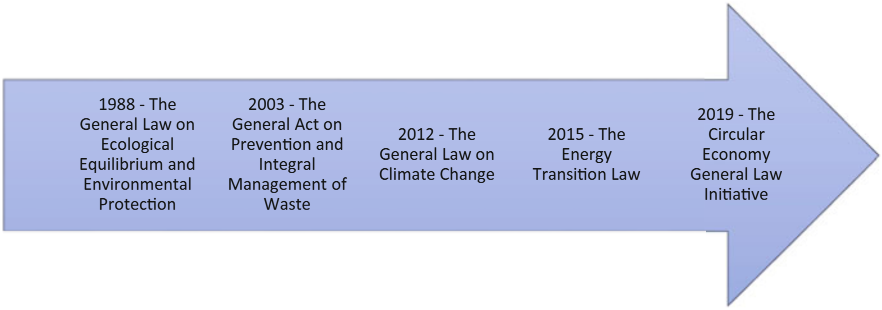


Fig. 8.1 Evolution of Mexican regulation that incorporates the adoption and implementation of circular economy. (Source: Prepared by author)

Moreover, governmental actions to implement CE strategies are also taken at subnational levels; Mexican states and municipalities have issued more than 20 regulations on the management and marketing of single-use plastics.

So far, CE actions and strategies adopted by both government and international aid have been described briefly in the above paragraphs, but considering the Mexican context, CE implementation should follow a "just transition" approach (Schroder 2020) with social equity, avoiding that traditional inequitable living conditions perpetuate. Taking this into account, a CE just transition shall include citizen involvement. But how aware or interested are consumers in Mexico?

The Hi-Cone multi-packaging company in its 2021 annual report informed on the public understanding of the CE concept. This study consisted of an online survey applied to 5000 adults (older than 18 years old) in Mexico, Spain, the UK, and the USA from October 29 to November 10, 2020. In Mexico, 1009 adults participated, and results indicated that there is a low level of public understanding regarding CE and only 35% of the interviewees recognized the concept. Despite this, most respondents highlighted the relevant role of consumers in successful plastic recycling; 73% of the survey respondents attributed recycling's responsibility to consumers, while 72% assigned it to product manufacturers.

Given these results, one might wonder how likely is it that Mexican consumers will recycle their waste? To answer this question, it is necessary to check the first Hi-Cone annual report. That study was developed using an online survey applied to 5509 adults in Mexico, Spain, the UK, and the USA from November 12 to 21, 2019. In Mexico, 1002 adults participated. Fifty-eight percent and 72% of them declared they recycled in their homes and in public spaces, respectively. Only 12% of the interviewees declared they recycled all plastics in their homes and public spaces. Sixty-two percent of the respondents declared they did not know how to recycle some types of plastic containers. Hi-Cone studies revealed that there is a need of continuing education and access to programs and recycling facilities for Mexican consumers to help in implementing the CE model in the country.

Given the current effervescent activity on the implementation of the CE model in Mexico, one might ask: What is the status of the adoption and implementation of CE ideas in Mexico? In which sectors has the CE model been successfully implemented? Is this transition solid and to the longer time? Which gaps are present in the Mexican sector? To address these questions, the objective of this document was to review the implementation of CE measures in the Mexican sectors through a bibliometric analysis on thematic documents in Spanish and English as well as through a review of the contents of web pages of corporations implementing CE strategies. This chapter is organized in four sections starting with a brief description of documents' source of data for bibliometric analysis; that method is also explained there. The second section presents results, and these are discussed. The fourth segment summarizes conclusions and present recommendations.

8.2 Materials and Methods

Data collection was divided into three sub-stages. First, data were retrieved using the phrase "circular economy in Mexico" from sources such as Dialnet, ScienceDirect, SciELO, and Google Scholar in both languages English and Spanish; to the resulting database, the documents included in the literature review in Muñoz-Meléndez et al. (2021) were added. The second sub-stage consisted of data loading and converting to a Web of Science format as a plaintext file—a TXT file. The last sub-stage was data cleaning to detect duplicate and misspelled elements. The resulting database was comprised of 28 registries; these are detailed in the "References" section included at the end of this document but are mixed with the rest of references used here; to identify the references included in the database, the symbol "#" was added at the end of the specific record.

The bibliometric (data and visualization) analysis was carried out using the Bibliometrix R-package (Aria and Cuccurullo 2017) version 3.1.4 in RStudio 2021-09.0 "Ghost Orchid" for macOS. The Bibliometrix package was used through the "Biblioshiny" web interface. This study included descriptive analysis and basic plots, bibliographic network matrices' characterization, descriptive analysis of network graphs on author's keywords and abstract, and visualization of bibliometric networks, in special author's keyword co-occurrences, and, finally, co-word analysis by means of conceptual structure maps.

Additionally, a review was developed on the contents of web pages of corporations operating in Mexico that self-reported the implementation of CE actions in their processes.

8.3 Results and Discussion

Table 8.1 displays the main information about the data collected. As seen, the research on the topic has a short time span going from 2017 to 2021 with an annual scientific production peaking by 2019, as shown in Fig. 8.2. The modest body of

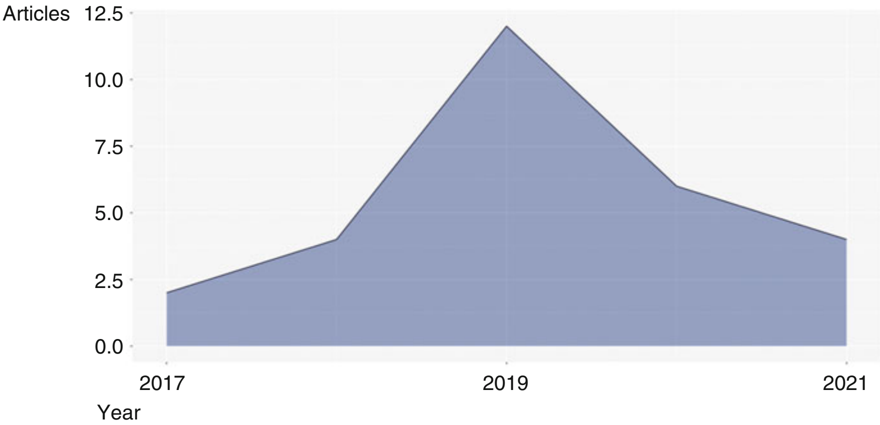
Table 8.1 Main information on data collected

Description	Results
Time span	2017:2021
Sources (journals, books, etc.)	21
Documents	28
Average years from publication	1.79
Average citations per documents	1.571
Average citations per year per doc	0.4696
References	1236
Document types	
Article	14
Book	1
Chapter	7
Conference paper	1
Report	3
Thesis	2
Document contents	
KeyWords Plus (ID)	0
Author's keywords (DE)	89
Authors	
Authors	51
Author appearances	63
Authors of single-authored documents	3
Authors of multi-authored documents	48
Authors' collaboration	
Single-authored documents	14
Documents per author	0.549
Authors per document	1.82
Co-authors per documents	2.25
Collaboration index	3.43

Source: Prepared by author

literature accumulated so far are mainly research articles in several journals, followed by book chapters published mainly by Springer. The most important journal used as source of information was the *Journal of the Cleaner Production*. However, frequently cited references are Ellen MacArthur Foundation's documents such as "Towards the Circular Economy (2013)" and "Building Blocks for Circular Economy (2015)."

Figure 8.3 shows word clouds—visual representation of words with greater prominence because they appear more frequently—for (a) the author's keywords and (b) abstract using bigrams, which is a sequence of two adjacent words. Figure 8.3b reveals that waste management is the main sector related to CE. Pursuing a clearer visualization, abstract in bigrams was plotted as a tree map—a map implementation that keeps its entries sorted according to the natural ordering of its keys—see Fig. 8.4. From this, it could be noticed that waste management is indeed



Source: Prepared by author

Fig. 8.2 Annual scientific production. (Source: Prepared by author)

Source: prepared by author

Fig. 8.3 Word cloud. (**a**) Author's keywords. (**b**) Abstracts using bigrams. (Source: Prepared by author)

the Mexican sector most related to CE, but considering abstract's terms covering 50% of all terms used in the diverse documents, all expressions contained in the classes listed up to the third column from left to right should be considered; when doing so, two other terms became relevant: climate change and business model.

If terms are displayed over time, it is possible to identify how those included in the abstracts have behaved in the analyzed period; see Fig. 8.5. As viewed, at the beginning of the period, interests focused on economic models to change later to waste management and transit more recently to urban solid waste and climate change.

Up to this point, the bibliometric analysis has been dedicated to the characterization of single or couple of words in author's keyword and abstracts, respectively. However, other relevant patterns may appear if terms are grouped in terms of how

Source: prepared by author

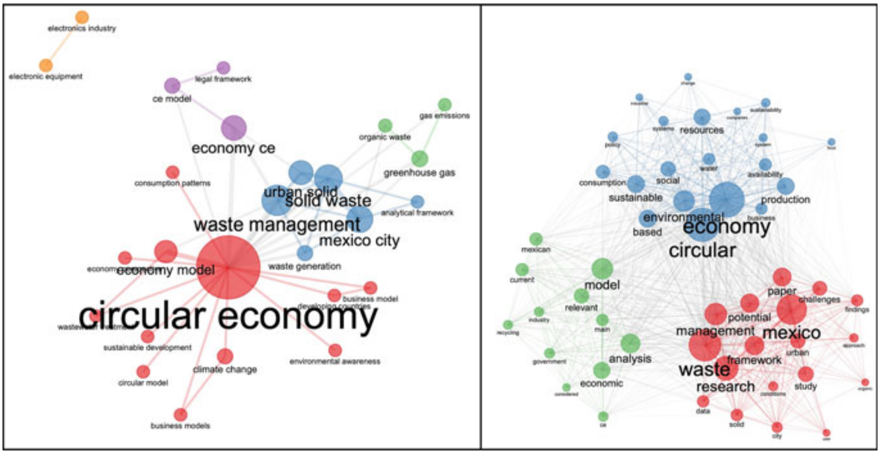
Fig. 8.4 Tree map of abstracts in bigrams. (Source: Prepared by author)

Source: prepared by author

Fig. 8.5 Trending topics from abstracts in bigrams. (Source: Prepared by author)

they strongly relate within the set of documents or records; this is if a co-occurrence analysis is applied. After this, such method was applied specifically on abstracts' unigram and bigrams; results are shown in Fig. 8.6a, b. As seen in Fig. 8.6a, when bigrams are used, five groups related to CE emerged; from these, a second sector besides waste management is revealed—the electronics sector; notice that it is largely isolated. Conversely, if single words are considered, three groups are displayed, and waste management appeared again as the main sector adopting CE actions in the country.

As part of the conceptual structure of a framework using the word co-occurrences, a dimensionality reduction technique in the bibliographic collection



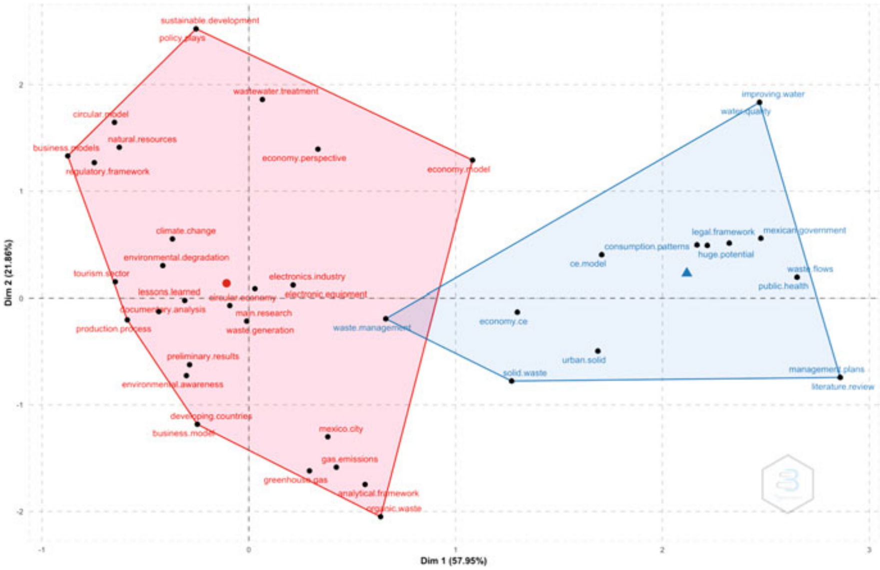
Source: prepared by author

Fig. 8.6 Co-occurrence network on abstracts. (**a**) Bigram. (**b**) Unigram. (Source: Prepared by author)

was applied, in this case multiple correspondence analysis (MCA); such analysis was carried out on uni- or bigram terms inside abstracts. Results identified two clusters interchangeably if uni- or bigrams were used; the former explained around 50% of the variance present in the collection, while the latter explained nearly 80% (see Fig. 8.7 where the two-dimensional map for bigram abstracts is shown).

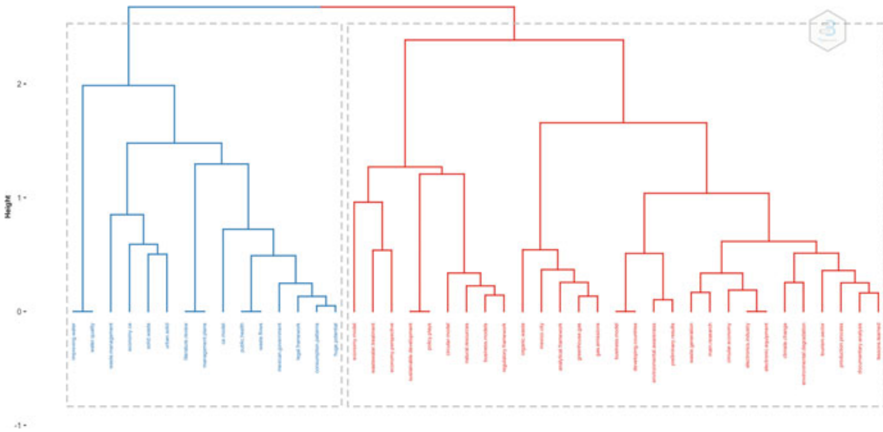
As sighted in Fig. 8.7, currently, research on the circular economy in Mexico are divided into two groups connected by waste management; these results confirm that this sector has been the most relevant in adopting and implementing the CE concept; inasmuch, association in Fig. 8.7 identified specific waste flows being managed such as urban solid waste. These terms are clustered together in the blue area; additional terms included are consumption patterns, management plans, and government; all of them are expected in a logical way to be together. Still more interesting is the inclusion of the term “water improvement and quality.” On the other hand, the pink area contains sectors such as “tourism” and “electronics industry”; this result suggests that such sectors have been investigated regarding CE implementation but not enough to be recognized as fully characterized; this condition is more clearly seen in Fig. 8.8, which depicts a topic dendrogram and where terms of such sectors are separated.

Up to this point, bibliometrics indicators have provided detailed information but limited to literature available. To complement this study, the analysis was extended to the content of web pages of corporations operating in Mexico that have reported the incorporation of circular economy actions in their processes; results are shown in Table 8.2. As seen, corporation actions in most cases are not exclusively designed for Mexico but are part of actions undertaken by corporations whenever they operate. In Mexico, actions are in a development phase; the most common activities are those related to the re-design of packaging content using recycled material, while



Source: prepared by author

Fig. 8.7 Conceptual structure map using multiple correspondence analysis on bigram abstract. (Source: Prepared by author)



Source: prepared by author

Fig. 8.8 Topic dendrogram using bigram abstracts. (Source: Prepared by author)

few activities are related to natural resource conservation particularly water and energy. Nonetheless, corporation activities could help Mexico to transit to the CE model, as corporations are likely to continue implementing CE measures on their own terms.

Table 8.2 Corporations implementing circular economy actions in Mexico

Corporation	Actions
Unilever[a]	In 2017, as part of its Sustainable Life Plan, this corporation committed itself to reduce one third of the plastic containers used in over the last decade, by 2020; this measure will be achieved by replacing the use of up to 50% of virgin plastic for recycled material
	Unilever Mexico also agreed to reduce by 2025 at least 25% of the plastic volume used in 2015. Finally, Unilever stopped landfilling waste generated in their operations in 2015
	By 2019, Unilever Mexico declared that it will foster the concept of CE through educational programs directed to communities, in particular children and youth populations
ECOCE, Ecolana, Dow, Grupo AlEn, Grupo Bimbo, Grupo Modelo, Herdez, Industria Mexicana de Coca-Cola, Kimberly-Clark de México, L'Oréal, Nestlé México, PepsiCo Alimentos Mexico, Recupera, Smurfit Kappa, Tetra Pak, Unilever y Walmart-Mexico, and Center America[b]	In 2019, the initiative "Reciclamanía" was launched to collect and recycle packaging and containers from consumers. This initiative has had two exercises
	The first was held in 2019, and then 1800 clients recycled more than 3300 kilograms of materials
	The second exercise was organized in 2020 under the name "Reciclamanía Evoluciona"; then six recycling points were installed in selected places in Mexico City and other five states; in those recycling points, the material allowed to be collected were glass, plastic PET, HDPE, LDPE, BOPP, paper, cardboard, metal cans, coffee capsules, toothpaste tubes, and toothbrushes. This action was declared permanent by November 2020
Nestlé México[c]	In 2021, this corporation announced the opening of a plant for recycling plastic to a food grade level. The final capacity will be of 26,000 tons
Coca-Cola Co.[d]	By 2019, this corporation reiterated its compromise to produce 50% of plastic bottles using recycled material by 2030. This corporation reported that more than one million fridges have operated using natural refrigerant gases reducing up to 99% of greenhouse gas emissions (GHG)
	Coca-Cola Co. declared that it will support education and environmental awareness programs to advance the circular economy understanding
PepsiCo Mex[e]	By 2018, this corporation reported that 92% of waste generated in comparison with the

(continued)

Table 8.2 (continued)

Corporation	Actions
	volume produced in 2015 was reduced through its program Zero Waste to Landfill
Jumex[f]	In 2018, this corporation reported working together with the CHEP company to reuse their pallets reducing 3500 CO_2 tons
La Costeña[g]	In 2018, it announced the re-design of tin manufacturing and reported they have their own wastewater treatment plant. In addition, the corporation has a biogas plant and solar panels; both infrastructures generate enough energy to reduce 30% of the electricity consumption
Heineken Mx[h]	By 2016, this corporation join Circular Economy 100, an Ellen MacArthur Foundation program
	In 2019, Heineken Mexico reported 17% reduction of water consumption and 16.5% on the electricity consumption. There was also an increment of 11% in the use of thermal energy
Grupo Bimbo[i]	In 2021, this corporation reported the use of pallets built with recycled packaging, 20% from post-consumption and 80% from recovered hard plastic
Tajin	According to Preciado-Cordova et al. (2021), this corporation uses plastic containers built with 100% recycled material
Walmart	Rincón-Moreno et al. (2020) reported that one Walmart store located in the Metropolitan Area of Mexico City has Zero-Waste-to-Landfill strategies into the ReSOLVE framework on the management of food waste. Authors reported that through such method, the retail store managed to reduce 40% of costs and estimated a theoretical digestion process that could yield on average 11,054 CH_4 liters per day
PetStar	Camara-Creixell and Scheel-Mayenberger (2020) described the PetStar sustainable business model based on CE principles. Authors reported that 72% of plastic packaging are never recovered at all and that with the PetStar model, 80,000 tons equaling to 70% of PET bottles are recovered and taken to their plant in Toluca Mexico State where bottles are converted into resin. By using resin from recycled PET process, 78% GHG emissions are reduced against using virgin resin. In addition to such benefit, the recycling plant gives employment to 1000 people and indirect benefits to 24,000 scavengers

(continued)

Table 8.2 (continued)

Corporation	Actions

Source: Prepared by author
[a] https://www.unilever-northlatam.com/news/press-releases/2017/unilever-e-compromete-a-utilizar-envases-plasticos-100-reciclables-para-el-2025/
[b] https://porunplanetamejor.com.mx/proyecto/reciclamania-evoluciona/
[c] https://www.nestle.com.mx/media/pressreleases/nestle-greenback-y-enval-instalan-planta-en-mexico
[d] https://coca-colafemsa.com/noticias/economia-circular-empaques-coca-cola-femsa/
[e] https://www.pepsico.com.mx/sustentabilidad/fundacion-pepsico-mexico
[f] https://www.il-latam.com/blog/projections/jumex-y-chep-15-anos-de-colaboracion-logistica-sustentable/
[g] https://www.elempaque.com/temas/La-Costena-95-anos-de-innovacion-en-envase+124947
[h] https://heinekenmexico.com/informe-sustentabilidad/holistica/piensa-circular/
[i] https://heinekenmexico.com/informe-sustentabilidad/holistica/piensa-circular/

8.4 Conclusions and Recommendations

The objective of this document was to learn about the status of the implementation of CE measures in Mexican sectors. To achieve this objective, two main analyses were utilized. The first was a contextual analysis, same that was carried out by means of a couple of short reviews on Mexican regulations that may help CE implementation and on public perception about CE understanding. The second was a type of content analysis; more properly, two methods were used: (1) a bibliometric analysis on thematic documents in Spanish and English, such as articles, book chapter, books, reports, and thesis, and (2) a review of the contents of web pages of corporations implementing CE strategies.

A contextual analysis exposed that (a) the presence of international aid to promote CE implementation in the country, but caution should be applied for the dedicated support funds to be transparent and responsible institutions involved in the transaction should be accountable, to ensure that just transition funds reach those affected as intended as pointed out by Schroder (2020), additionally a mechanism that avoids full dependency on external funds to allow CE model adoption, should be created, (b) Mexican government at national and subnational levels have issued regulations to support CE adoption, but not an exclusive initiative, at least not at Federal level, yet some States have emitted dedicated laws although most are regulations focus on one-single-use plastics ban; this unbalance situation could trigger chaos and remarks the need to set up a national strategy on CE; and (c) a review of the Hi-Core studies showed that Mexican consumers are not familiar with the CE thinking but are willing to recycle—at least—plastics, such disposition should be used to help implementing the CE model in the country. Hi-Core studies also indicated that Mexican consumers need access to programs, education, and recycling facilities.

It was revealed through (a) the bibliometric analysis that the most advanced sector implementing CE model is waste management and that there are limited diagnoses on tourism and the electronics industry and (b) the web page content analysis that the CE actions in corporations are not exclusively designed for Mexico and they are in development phase, with the most common activities relating to the re-design of packaging material using recycled material, while few activities are related to natural resource conservation.

As waste management plays such an important role at this point in the CE implementation in Mexico, it should be remarked that in recycling activities intervene informal circuits which operate or tend to do so in a way that does not necessarily support CE or even sustainable recycling practices as they seek to profit low-hanging fruit, therefore reinforcing open system practices (Botello-Álvarez et al. 2018; Guibrunet et al. 2017; Delgado Ramos 2019), yet there is room for working with informality to move to the adoption of CE practices as in the PetStar case detailed by Camara-Creixell and Scheel-Mayenberger (2020); furthermore, addressing informality could help to implement the just CE transition, more than promoting "green jobs," but improving workers' labor conditions while strengthening partnerships with the private as well as with the social and informal sectors. Considering the regional differences along the country and their capacities and potentialities, different types of interventions, partnerships, actors, and actions will be needed. In the case of Mexican cities, local governments can play a fundamental role in accelerating CE transition.

There is a clear need to move the CE thinking to other areas besides waste management that at the time is almost exclusively directed to the plastic market and other recoverable materials and in a lesser extent to urban solid waste. For the adoption of the CE model in other sectors, adequate support and incentives are needed. It must be acknowledged that there are incipient investigations on the water sector—which could be of great use in the arid northern part of the country—so far, its impact for the tourism consumption is already being questioned as demonstrated by the Cruz-Vicente and Agaton-Lorenzo (2019) study or its role in the urban water supply as presented by Casiano et al. (2018) and Gleason-Espindola (2018). At this point, breakthroughs in bioeconomy are very much at the diagnosis phase, particularly on the biorefinery topic, as is the research on the electronics industry, specifically mobile phones.

Results from this study suggest that Mexico is implementing the CE model to achieve sustainable development but also to tackle climate change. If successfully implemented, the country could certainly advance its international commitments such as the Agenda 2030 and the Paris Agreement.

Mexico is on the right path for the adoption and implementation of CE but still taking early steps but accelerating its pace then it is appropriate time to provide recommendations, those identified by Muñoz-Meléndez et al. (2021) are recovered and repeated here:

- Set up a national strategy on circular economy.
- Provide logistics and support for small- and medium-sized enterprises (SMEs) to adequate their process and products into the CE model.

- Provide adequate channels for collaboration between large corporations already implementing CE measures and SMEs.
- Support educational and awareness campaigns for other wastes and residues that could be used in different sectors within the CE thinking.
- Propose forms to support research and development (R&D) on CE within the academic sector and in partnership with the industry; as investment in science and technology is low, the federal investment has not been consistent in reaching the 1% stipulated in the General Education Act in more than a decade. The budget presented for academic and scientific production for 2020 amounted to 0.8% of the federal budget (Garcia-Bulle 2020).

In comparison to the adoption of the CE model in the LAC region, Mexico has advanced on the CE implementation in waste management and recycling sector and some industries and large corporations, but the country does not show progress in the mining and extractives sector. And this lack of address is key to make a long, solid, and long-term transition, because Mexico and LAC for that matter based their development through exports of primary products through extractivism despite that such model is vulnerable to external economic cycles dictated by high-income countries and adverse terms-of-trade effects (Altomonte and Sanchez 2016). LAC countries continue relying on the extractive model because the abundance of natural resources in the region, despite that extraction of primary goods do not translate into wellbeing; this is the relation between exploitation of natural resources and economic growth is not directly proportional (Rodríguez-Arias and Gomez-Lopez 2014). Moreover, the extractive model has been considered exhausted recently (Gudynas 2020).

Furthermore, the extractive model has contributed to the stagnation of the LAC region and Mexico alike, as seen in the lack of technological innovation, inequality gap, poverty, environmental degradation, and social conflict. There is an urgent need to transform the current economic development model practice in Latin America; however, any transformation will bring new problems that should be addressed now but with a long-term vision in mind and incorporating the unique social conditions unique to the region; any change to the current economic model should consider local conditions, embrace changes in an integral way, and tend to become semi-autonomous in time. LAC countries should first appropriate and later innovate technology solution under the local context and mainly incorporating their limitations. This necessarily means that Latin American governments stop envisaging the development of megaprojects as the only way to achieve development (Muñoz-Meléndez and Cano 2021).

Mexico and the rest of Latin American countries face challenges; being the most urgent are a change on its current economic model and the CE adoption and implementation should be done under what Muñoz-Meléndez et al. (2021) denominate "hybrid model" or one connecting a just and sustainable transition agenda, with job creation and development in order to fully explore CE potential; one with new ways of thinking and planning, with interinstitutional coordination, and with governance schemes; or one that embraces diversity present in a developing country such as Mexico and considers Mexican consumers not only to modify the consumption pattern of goods. Thus, in the transition of linear extractive to a CE model, Mexico should fully embrace technological innovations while innovations are deployed on social and organizational innovations. However, this description in size and degree at adopting and implementing CE could sound as a bunch of good wishes under unreal aspirations. Could Mexico overcome risks and adopt CE in a beneficial and equitable way at local levels?

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Part IV

Circular Economy Adoption in Industries

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9 Circular Manufacturing Transformation: Manufacturing Perspectives, Examples, and Experiences from Implementation of Circular Economy in Asia

René Van Berkel

Abstract

Beyond its compelling logic, circular economy gives rise to divergent perspectives and interpretations, which hamper acceptance and collective action towards our common goal to combat climate change, loss of nature, and waste and pollution. Transformative physical change in products, materials, and technologies, or manufactured goods, is required, in short a circular manufacturing transformation. Such transformation is a process that results in resource circularity, resource efficiency, and/or resource substitution (outcomes), through the implementation of circular manufacturing solutions (outputs) in the design, manufacturing, use, and end-of-life management of goods and services developed and implemented through the purposeful conduct of input activities, particularly entrepreneurship, systematic design thinking, and innovation. Indeed, this process is happening as illustrated for the case of textile and apparel manufacturing, where circular manufacturing solutions sprout up within firms operating in successive parts of global value chains. There is a solid experience base to ground the circular manufacturing transformation particularly in the areas of resource-efficient and cleaner production, industrial and urban symbiosis, green chemistry and engineering, and waste to wealth. Capacitating and supporting firms as agents of the circular manufacturing transformation is warranted.

Keywords

Circular economy · Resource efficiency · Industrial symbiosis · Manufacturing · Innovation · Productivity

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9.1 Circular Economy Perspectives

The 2020s have brought new urgency to the green agenda, as earlier projections of scientists about the likely impacts of global environmental and climate change started to become an everyday reality. The World Meteorological Organization (WMO) found that the global climate had in 2021 already warmed by 1.1 °C since the start of the industrial era (WMO 2022), an alarming fact in view of the assessment by the Intergovernmental Panel on Climate Change that 1.5 °C global temperature rise since pre-industrial time appears the climate tipping point (IPCC 2018). The World Health Organization (WHO) estimated that 99% of global population is exposed to unhealthy air (WHO 2022), and many indeed are regularly exposed to hazardous levels of air pollution, including in large parts of South Asia. Moreover, plastic litter has become omnipresent in even the most remote corners of the world whether on land, in rivers and lakes, or in oceans (UNEP 2021a, b, c). The United Nations Environment Programme (UNEP) presented paramount evidence for the interrelatedness of global environmental threats in the form of a triple manmade planetary crisis that is on us, through climate change, loss of nature and biodiversity, and accumulation of pollution and waste (UNEP 2021a, b, c). Collectively, these pose a threat to the decency and sustainability of human life on planet Earth.

Even in purely monetary terms, if we forego nature's intrinsic value from the equation, the costs of current environmentally unsustainable practices are enormous. The Lancet Commission on Pollution and Health estimated welfare losses due to environmental pollution at more than US$ 4.6 trillion per year, 1.5 times the size of the Indian economy or 6.2% of global GDP (Landrigan et al. 2017). The economic costs of global warming are estimated at more than US$ 1.2 trillion per year, reducing the world's economic output by 1.6% annually. Various other, yet less visible, environmental threats may cause loss and damages in similar orders of magnitude.

The triple planetary crisis is profoundly manmade and fundamentally caused by the escalating use of natural resources, including energy, materials, water, land, etc., beyond the Earth's carrying capacity. Fundamental and transformative change in the extraction, use, and disposal of natural resources is required to decouple economic development from the increased use of natural resources and from the increased generation of waste, effluents, and emissions (UNEP 2021a, b, c), put it simply, doing *more* (economic activity) *with less* (resource use and environmental impact) and with the intent of contributing *more* (well-being) to people and society. Closing material cycles is an appealing conceptual way for doing so, which has given rise to the emergence of the concept of circular economy. As a concept, circular economy aims to replace the prevailing linear take-make-throw economic model with an alternative circular take-make-recover economic model that endlessly retains products and materials and their economic value in consecutive use cycles.

Circular thinking has origins in the field of industrial ecology (van Berkel 2007a, b) and demands that (a) natural capital is preserved and enhanced, (b) products and materials are kept in use, and (c) wastes and negative externalities are designed out of the system (Ellen McArthur Foundation 2015). Circular economy has immediate appeal as it presents a powerful metaphor of natural cycles in ecosystems as a de facto normative model for cyclic material and resource flows in the industrial production and consumption systems of an economy. This metaphorical appeal though hides a great deal of divergence among and between both enthusiasts and critics, along three main entry points: circular solutions, circular innovation and product design, and circular business models.

Circular solutions concern the practices that contribute to achieving circularity. Most commonly, the three well-established value *recovery* practices of reduce, reuse, and recycle (3R) are expanded with the value *retention* practices of repair, refurbishment, and remanufacturing (IRP 2018). Value retention is aimed at returning a discarded product (or waste) into a fully functional product to be used for its originally intended purpose by fixing of a specific fault (in case of repair), by modification to restore performance and functionality (in case of refurbishment), or by industrial restoration to original as-new condition and performance (in case of remanufacturing). Both (material and resource) recovery and (value) retention practices are principal solutions for discarded or dysfunctional, end-of-life products, components, and materials. Yet a broader circular orientation is both necessary and possible to recover and revalorize all previously discarded natural resources, including water, energy, and production and distribution wastes.

Any circular solution involves a technical innovation of some sorts at the level of materials, technologies, processes, and/or products (Ritala et al. 2023). Such technical innovation is constrained by technology opportunity and the ability to utilize this available technology opportunity fully in circular products, processes, and materials. Technology opportunity expands through research and innovation that requires specific focus to accelerate circular innovation. Established methods for technology and innovation road mapping (Cobra et al. 2021) can be deployed to shape research and innovation trajectories that have potential to deliver the required sustainable, carbon, land and water neutral, and nature positive, circular production and consumption systems. Product development beneficially utilizes technology opportunity, which greatly benefits from design thinking, or systematic and industrial design. In essence, managers work therein iteratively towards solutions using an abductive approach that emphasizes incremental changes and assessment of outcomes, followed by further adjustments, through five formally structured iterative steps: empathize, define, ideate, prototype, and test (Hoffstetter et al. 2021). This maximizes the interplay between technology opportunities, product use case, business case, and social and environmental impacts along the value chain. Realizing circular innovation opportunities calls for tailored design competencies (Melles et al. 2022). These include designing systems that address life cycles and not just products that serve use cases; solution-oriented problem-solving and co-evolution of the problem and its solution; anticipation of future scenarios and possible solutions; making these visible and debatable by delivering representations and boundary objects; enabling reasoning and cooperation among people from different domains, disciplines, and perspectives; developing niche innovations and proposals that are then readily available when opportunities arise; and addressing social justice by offering human-centered and humane-centered perspectives and enabling stakeholders' participation (Melles et al. 2022).

Circular economy requires innovation beyond this technical level to include the logistical level of value chains and the organizational level of business models (Ritala et al. 2023). Business models generally concern ways to express how a company creates, delivers, and captures value. The discourse on business models for the circular economy focuses on ways circularity thinking can create and leverage new business and earning opportunities for start-up and established businesses. In a circular business context, value arises from the application of loop strategies, particularly narrowing, closing, slowing, and regenerating loops (Brocken et al. 2016). Narrowing the loop refers to using fewer materials and less energy per product; closing the loop essentially refers to post-consumer recycling; slowing the loop refers to product lifetime extension and avoiding unnecessary consumption; and regenerating the loop refers to cleaner loops and leaving the environment in a better state than previously. Each of these is applicable through different lenses (Ritala et al. 2023). The customer-centric lens considers a product or service offering to deliver new circularity value to the consumer. The firm-centric lens considers business processes to deliver new circularity value to the firm. The business ecosystem lens looks at business collaboration or partnerships to deliver circularity value to the business ecosystem in which the firm operates.

These divergent interpretations of circular economy by practitioners, scholars, innovators, businesses, and governments produce opposing assessments of its potential benefits, which in turn can hinder progress in acceptance and implementation. Three main narratives are prevalent—skeptical, optimist, and reformist (Leipold et al. 2022).

First, the optimist narrative takes circular economy as a driver for sustainability transformations and indeed considers it as the only form of human development within planetary boundaries (Leipold et al. 2022). This is a reflection and expansion of pre-existing ecological modernization thinking (Hoffstetter et al. 2021). The narrative focuses on the seemingly limitless benefits achieved in circularity case studies and argues to replicate and scale up best practices and techniques, using market forces and economic policy.

Second, the skeptical narrative observed that the circular economy lacks an economic theory that can pragmatically guide the transition from the prevailing neoclassical model towards one that would drive the transition towards a sustainable circular economy (Velenturf and Purnell 2021). The uncritical application of recycling and other circular solutions overlooks, firstly, the negative environmental and social impacts from recycling processes, including energy requirements, residual waste generation, dispersion of hazardous substances and occupational and community health (Chen et al. 2023), and, secondly, the risks associated with perpetuating additives and contaminants into new use cycles. Increases in consumption can wipe out the relative improvements in materials and resource efficiency achieved with circular economy solutions, known as the rebound effect. An integrated assessment of net environmental benefit is required to ensure the reduction and circulation of resource use, minimization of the transfer of environmental impacts, and mitigation of rebound effects (Hoffstetter et al. 2021). By this skeptical narrative, the circular economy therefore in many ways appears as a practitioner-oriented business, government, and industry *light* version of a truly environmentally sound and sustainable economy (Saavedra et al. 2018).

Third, the reformative narrative argues that the circular economy has transformative potential but only if social and environmental boundary conditions are met (Leipold et al. 2022). It acknowledges that good policy design and implementation can promote the circular economy concept to inspire, ignite, and advance the sustainability transformation, provided this policy removes status quo interests and addresses potential rebound effects or burden shifts. The reformative narrative avoids the uncritical enthusiasm on the general applicability and benefits of the resource recovery and value retention processes, yet instead assesses net social and environmental benefits of specific circular economy solutions, within their respective application contexts. Simultaneously, it recognizes the strong and imaginative appeal of the circularity metaphor as driver and shaper of innovation and design thinking leading to practical sustainability solutions. This positive appeal of circularity is, firstly, its holistic nature that addresses the triple planetary crisis in an integrated manner and, secondly, the realization that circles prevail because nothing goes to waste, which reinforces that nothing less than zero carbon, zero waste, and zero impact is sufficient to achieve sustainability outcomes. The reformists use circular economy as a shorthand for a circular transformation of the economic activity of production and consumption, not as a substitute economy.

9.2 Circular Transformation of Manufacturing

In a circular economy, households and other consumers sustainably and responsibly consume circular products and services supplied and manufactured by businesses and industries, taking into consideration government policy, market opportunities, available technology and capabilities, and other enabling and shaping factors. Hence, a circular economy is an industrial economy, as profoundly articulated by the United Nations Industrial Development Organization (UNIDO): "circular economy is an industrial economy that routes materials, parts and products back into use several times and creates more value and less waste. It is an alternative, that maintains value for as long as possible, designs products to last, and minimizes the generation of waste. It is achieved through integration of circular economy practices in traditional linear value chains" as depicted in Fig. 9.1 (UNIDO 2019a, b). This definition specifies circular economy practices and promotes these as replicable—or even generic, universally applicable—solutions to re-engineer linear value chains into circular value loops. This portrays the earlier referred optimist narrative, which is being critiqued as a practitioner-oriented business, government, and industry *light* version of a truly environmentally sound and sustainable economy (Saavedra et al. 2018).

In the reformative narrative, circular economy instead encompasses transformation process of the economy. This process approach is elaborated using the

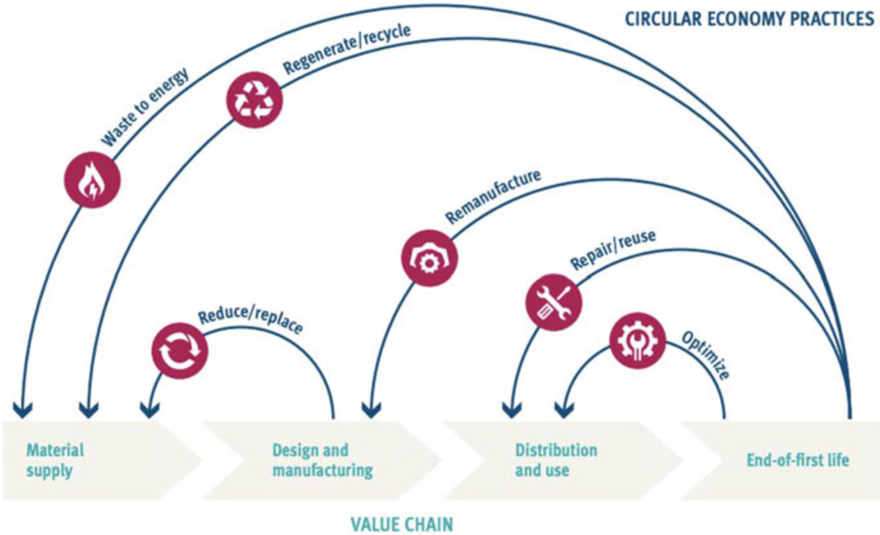


Fig. 9.1 Circular economy practices in the value chain (Adapted from UNIDO 2019a, b)

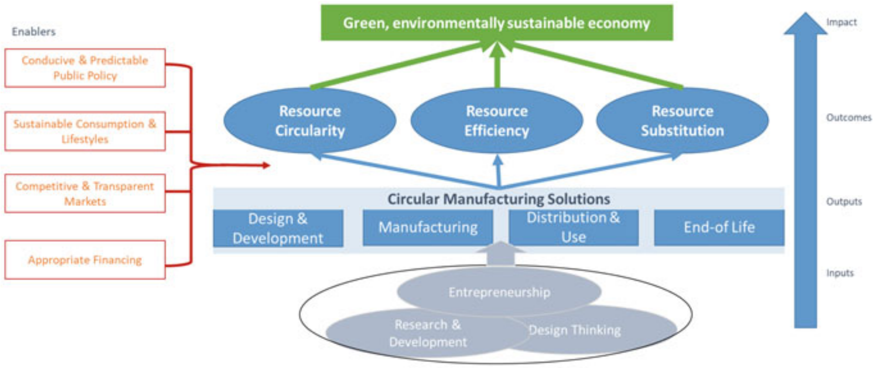


Fig. 9.2 Circular transformation of manufacturing (elaborated by author)

established input-output-outcome logic, as illustrated in Fig. 9.2. This offers a narrative for turning circular economy input activities (entrepreneurship, design thinking, and innovation) into circular manufacturing solutions along the product life cycle, which are more circular and resource efficient, facilitated by enablers in policy, markets, consumer behavior, and financing.

At the *impact* level, circular economy targets a production and consumption system that is in long-term balance with nature, resources, and ecosystems on which it ultimately depends, in short a green, environmentally sound economy. This involves a (technical) transformation in the use of natural resources in products, processes, and materials. Such technical transformation has distributional impacts as some sectors, regions, job categories, investors, etc. stand to benefit while others may lose. In other words, the technical transformation will cause a socioeconomic transition that requires consideration, planning, and management, to ensure that no one is left behind (ILO 2015). This just and inclusive transition is important as a boundary condition for the circular economy, however not the driving force nor a principal target.

Circular economy targets three intended *outcomes*. These are (1) *resource circularity* (achieving the perpetual use and reuse of end-of-life materials and other discarded resources), (2) *resource efficiency* (reducing the generation of waste materials through efficiency in the design, manufacturing, distribution, and use of products), and (3) *resource substitution* (selecting and using resources that are easily returnable into natural or technical cycles) (modified from van Berkel and Fadeeva 2020). These three are not mutually exclusive, and indeed, specific circular solutions may contribute to two or three outcomes. Even though these outcomes bear resemblance to the earlier referred circular business loop strategies (Brocken et al. 2016), these have here a technical interpretation and extended coverage. The circularity outcome best corresponds to the closing loop business strategy. However, it further emphasizes the need for system solutions that involve multiple and ideally even perpetual use and recovery cycles that take due consideration of the fate of all the discarded materials, water, and energy, with due consideration of the fate of contamination with potentially hazardous materials, such as additives in plastics or heavy metals in fly ash. The efficiency outcome includes the slowing and narrowing loop business strategies, which both result in lower life cycle resource use and waste generation per unit of product service. Such efficiency is though not exclusive to narrowing or slowing the loops and can indeed be achieved in other ways, e.g., reinventing the loops (alternative products, technologies, and consumption systems) or compacting value chains and products (elimination of unnecessary steps (including transport) and product features). The substitution outcome focuses on the selection of production inputs that maximize the sustainable use of renewable and circular materials, energy and water, whereas its apparent comparator regenerating business strategy focuses on improving the state of nature, which is beyond the realm of influence of manufacturing.

Circular manufacturing solutions achieve these three outcomes and are thus the *outputs* of a circular manufacturing economy. These are the new, innovative products, technologies, materials, logistic and use systems, and other artifacts that deliver improvements in resource circularity, efficiency, and/or substitution. Practically circular manufacturing solutions can originate at different stages in any product life cycle. One could conceptualize this as life cycle lenses for the identification and development of potential circular solutions. There are consecutive lenses for product design and development, for manufacturing, for distribution and use, and for end-of-life management. With the dominance of global value chains, these stages are increasingly further fragmented and globally dispersed, adding a further layer of complexity towards the necessary coordinated implementation of circular manufacturing solutions (see, e.g., Hoffstetter et al. 2021).

These circular manufacturing solutions originate in the purposeful application of research, development, and commercialization (development and application of new knowledge), design thinking (creative, collaborative, and iterative problem analysis and product and solution development), and entrepreneurship (identification and realization of business value)—these are the *input activities* to the circular economy. None of these is unique to circular economy; however, their focused application to achieve the resource circularity, efficiency, and/or substitution outcomes puts the circular economy in motion.

Enablers influence this process of development and realization of circular manufacturing solutions—their presence facilitates circular economy outcomes, and their absence presents barriers thereto. Four sets of mutually reinforcing enablers are critical, respectively, public policy, (sustainable) consumption and lifestyles, markets, and financing. Public policy for circular economy invokes regulatory, economic, information, education and research, and cooperation instruments (CSCP 2008), with potentially a multi-pronged focus (adapted from van Berkel (2018)): firstly, to discourage and/or ban the disposal of any wastes and the use of virgin and non-renewable resources; secondly, to encourage and create markets for products with sustainably sourced renewables and environmentally sound recycled, recovered, and revalorized wastes; and thirdly, to encourage and de-risk innovation and pivoting of new products and business models. The market economy is driven by customer demand from individual consumers as well as institutional buyers in government and business, and greater awareness of and adoption of sustainable consumption and lifestyles will hence enable circular economy. Markets need to ensure that circular features are verifiable and transparent and technical standards (e.g., building codes, fuel specifications, etc.) do not distort in favor of established resource-inefficient and linear products. Circular manufacturing solutions require investments and hence are critically dependent on access to financing that is appropriate and affordable to the specifics of the circular business case in terms of, e.g., risk profile, tenure, collateral, etc.

The complex and disperse nature of current manufacturing with its inherent interdependencies between firms and interlinkages of value chains challenges the operationalization of this circular transformation of manufacturing. The linear value chains for different products or product groups converge and diverge repeatedly, and no single firm or other actor controls or even has the ability to influence the technical processes along the entire value chain that collectively determine the final product's resource use and wastage footprint. This implies that a grand design of the complete circular manufacturing system for any product is in practice unlikely to succeed. Instead, a circular manufacturing system is more likely to emerge as a bottom-up, organic, and iterative process of stitching together circular solutions that more or less independently emerge in consecutive design, manufacturing, distribution, and use stages. This already appears in practice for different product groups and subsectors, as illustrated in Box 9.1 for the apparel value chain. Even though it is from a circular economy perspective promising that circular solutions are sprouting up across manufacturing value chains, the policy and business challenge remains to bring greater focus and connectedness between these individual and somewhat piecemeal solutions, in order to accelerate the circular economy transformation at large.

Box 9.1 Sprouting of Circular Solutions in Supply Chains: The Case of Apparel

The apparel value chain is exemplary both in terms of segregation between successive stages of design, manufacturing, distribution, retail, use and maintenance, and end-of-life disposal and in terms of its small production batches with short production cycles, driven by rapidly changing market demand, as typical for the predominant fast fashion. Apparel manufacturing involves the production of fiber (natural (cotton, linen, silk, etc.) or manmade (polyester, nylon, etc.)), textile chemicals (dyes, detergents, etc.), and accessories (buttons, zippers, etc.); spinning, weaving, or knitting and coloring and finishing of fabric; and garment making, finishing, and packing. Each stage has its own environmental and socioeconomic impacts, however with well-recognized hot spots (UNEP 2021a, b, c). Greenhouse gas emissions are dominant in the wet processing of fabric and—to a lesser extent—garment finishing, production of manmade fibers, and laundering in consumer phase. Water use is dominated by natural fiber production and laundering by consumers, whereas the use and release of hazardous chemicals in textile processing and garment finishing is most critical for water pollution and impacts on human health and ecosystems. Microfibers originate in the main from surface wear during the use phase and contribute to marine pollution with micro-plastics. Circular solutions are emerging at each of the main stages of the fashion life cycle (see, e.g., WRAP 2023).

Fashion design is critical to increase the actual number of use cycles by consumers (to slow down the rapid use and disposal of clothing and fashion) and to enable efficient repair, recovery, and recycling. Durability is key, from the complementary angles of technical and emotional durability (WRAP 2017). Technical durability considers garment design and construction in order to create products that can resist damage and wear. It is impacted by technical factors particularly robustness of garment construction, resistance to surface wear, color fastness, and clear instructions for lifelong use, care, and repair and is most relevant to denim, casual wear, children's wear, inner wear, and sportswear. Emotional durability takes into account relevance and desirability to the consumer—e.g., does the item still fit and be to the customer's taste? It is impacted by socio-emotional factors concerning how the wearers feel about their clothing, including their comfort, aging, and style, and is key to extending the use of knitwear and tailored wear and occasion wear. Physical and—to a lesser extent—emotional durability can be improved with quality materials, best available techniques, skills, and design techniques. Their scope can be extended with new and emerging technologies, such as 3D printing

(continued)

Box 9.1 (continued)

which allows for on-the-spot manufacturing of single garments without waste, water use, and effluent generation. This is already revolutionizing niche segments in, e.g., occasion wear (see, e.g., Sun and Valtas 2016; Sculpteo 2023).

Each of the main natural and manmade fibers has its specific environmental footprint with fiber-specific circular-oriented innovations emerging. For example, for cotton, the emphasis is on reducing the use of fertilizers, pesticides, and water in cotton farming, through either organic farming (1.4% of global cotton production in 2022 (Textile Exchange 2022)) or better cotton practices (22% of global cotton production in 2020 (BCI 2018, 2021)) while also improving cotton fiber strength and length. In case of manmade fibers, significant progress is made in converting plastic waste into textile fiber. The Tiruppur cluster in India, for example, has become a manufacturing hub for the production of sport and leisure wear from recycled PET bottles (Clean Future 2020), while others are upcycling discarded fishing nets into office wear (Lezé 2023). Several innovators are producing new natural fibers, for example, from banana waste (e.g., Bananatex, Green Whisper), hemp (e.g., Hemptex), bamboo (e.g., Bagrotex), grass (e.g., Descatch), or seaweed (e.g., Keel Labs) (Fashion for Good 2023), and these natural materials are inspiring new fashion brands with dedicated e-commerce platforms (e.g., in India (IKKIVI 2023)).

Textile dyeing and printing is also seeing innovations in different directions to eliminate hazardous chemicals (driven by multi-stakeholder initiatives such as Zero Discharge of Hazardous Chemicals (ZDHC 2022)) and minimize water and energy consumption. Significant improvements are possible with established technologies by adopting chemical management and best available techniques to optimize dyeing and other finishing processes in connection with using best available and lower water and energy requiring dyestuffs and textile chemicals (NCPC 2018). Alternative dyeing processes emerge at commercial scale in niche segments. For example, waterless dyeing with supercritical CO_2, which eliminates the use of water and auxiliary chemicals and the generation of effluents, saves 63% of energy and achieves 98% dye uptake in polyester dyeing for sportswear (Dyecoo 2023). Solution dyeing which injects the dyestuff directly into the manmade fiber filament is already more widely commercialized by, e.g., Little King and LiPeng (WRAP 2023). Naturally colored cotton is nowadays available for longer-stapled reddish-brown and green shades, after it was first discovered by Sally Fox back in 1982 (Baratta 2021). Traditional practices of dyeing with locally available fruits, leaves, barks, etc. in the handicrafts sectors are being revived and optimized to achieve higher color fastness, for example, for silk dyeing (UNIDO 2013). KBCols manufactures bio-colors for textile dyeing through extraction from

(continued)

Box 9.1 (continued)

industrially grown microorganisms selected from India's vast biodiversity, and Hues established a process for garment dyeing in 15 shades with waste from ice-tea manufacturing in Sri Lanka (Fashion for Good 2023).

Garment making is the largest source of pre-consumer textile waste, as between 10 and 25% of the fabric is lost in the cutting process, depending on garment design, pattern, and lot size. It has been traditionally down-cycled for stuffing in toys and upholstery, into cleaning rags, and/or as boiler fuel. Several community initiatives are using cutting waste for quilting and manufacturing of shopping and handbags, yet the volume remains small relative to the abundance of textile waste. More recently, textile cutting waste from readymade garment factories is mechanically recovered to fiber, color sorted, and re-spun into yarn for knitting or weaving and manufacturing of new garments, for example, in India under the brand name PureWaste® (PureWaste 2023). Garment finishing traditionally involves chemical and mechanical processes that add specific features, e.g., stone wash, water repellency, or otherwise. Biopolishing can replace traditional chemical or burning finishing (singeing) treatments as it uses cellulase enzymes (e.g., Novozymes) to modify the surface of cotton fabrics to prevent pilling, enhance color retention, and ensure smoother, softer, stronger fabrics that are durable to many washes, thus increasing the longevity of the fabric by at least 20% (WRAP 2023). In the denim sector, lasers can replace stone washing and open new opportunities for customized designs and shades, reducing on average chemical consumption by 85%, water consumption by 67%, and energy consumption by 62% (Denim Herald 2023).

Retail, including e-commerce, is a significant source of high-quality and high-cost textile waste, waiting for reduction, reuse, and/or recovery (Fashion for Good 2023). Digital technologies, particularly virtual and augmented reality and artificial intelligence, are being deployed in e-commerce to reduce returns that often turn unsellable, by helping customers to get the right size (e.g., PreSize) and visualize them wearing the garment in different environments (e.g., Perfitly). Digital platforms are also deployed to facilitate use of unsellable items by white labelling (e.g., Trove) and/or supporting renewal of unsold collections into vintage items (e.g., Renewal Workshop) or supply to secondhand markets (e.g., Reflaunt).

Changing consumer behavior is key to slow down their consumption of garments, which is addressed through media campaigns and information tools, such as the Love Your Clothes campaign in the UK (LoveYourClothes 2023). There is renewed interest in rental services, which existed for unbranded formal wear and are now expanding to cover a broader array of branded occasion wear, supported by platforms such as RE-NT and Lizee, and travel wear, supported by, e.g., Gibbon (Fashion for Good 2023).

(continued)

Box 9.1 (continued)

Recovery and recycling of post-consumer textile waste has been getting traction in recent years. Mechanical recycling combs the fabric back to fiber form, color sorts, and returns the recovered fiber for spinning and weaving into new fabric. It is a mature process and already deployed by select denim producers into post-consumer recycled denim, mixed in different quantities with virgin fibers (e.g., Arvind, Bossa, Kuyichi, MUD Jeans). Chemical recycling is well established to depolymerize the cellulose in pure cotton waste to produce a biodegradable pulp from which viscose is manufactured (by, e.g., Birla and Lenzing). This technology has further developed to accept cotton, cotton blends, and other textiles with high cellulose content for conversion into pulp suitable for manufacturing viscose and lyocell (Renewcell). H&M has developed store-sized garment-to-garment recycling machinery that turns the customer's old clothes into select new clothing items, which is on pilot basis operational in its flagship store.

As shown by this example for the apparel product life cycle, some technology opportunities and business models already exist, and more are developing in subsequent stages of manufacturing, distribution, use, and end-of-life management. Their outcome, in terms of actual improvements in resource circularity, efficiency, and substitution, however, depends on the coordination and matching of material inputs and outputs and technology choices between subsequent life cycle stages that take place in different firms operating dispersed in global value chains. Greening of global value chains has been on the agenda of leading firms and brands in the Global North (Hoffstetter et al. 2021). It has worked in the main as a top-down strategy with firm or multi-stakeholder voluntary sustainability standards with a strong focus on environmental and social compliance (UNFSS 2018). Despite noteworthy progress in greening global value chains, new impetus and methods are required to enable and empower supplier firms in the Global South to develop and implement circular solutions (Hoffstetter et al. 2021).

9.3 Experience Pillars Towards Circular Manufacturing

The full understanding of the transformative nature of circular economy for the manufacturing sector is still evolving. Equally though, there is two to three decades of global experience with the practical implementation of methods and practices that are contributing to the outcomes and impacts of circular economy as identified in the transformation model, visualized in Fig. 9.2. It is essential to ground-truth the further development and implementation of circular economy in manufacturing sector in the achievements made, methods and policies developed, and lessons learned with each of these—referred here as experience pillars. The following provides the genesis, overview, and illustrative business examples for select key experience pillars,

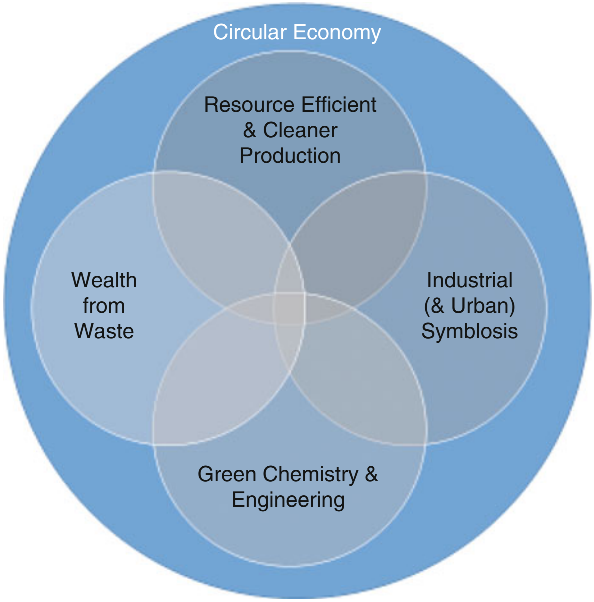


Fig. 9.3 Experience pillars towards circular manufacturing (author's elaboration)

particularly resource-efficient and cleaner production, industrial (and urban) symbiosis, green chemistry and engineering, and wealth from waste, as depicted in Fig. 9.3.

9.3.1 Resource-Efficient and Cleaner Production

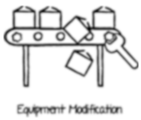
This term is an amalgamation and integration of different proven concepts and practices, such as cleaner production, eco-efficiency, pollution prevention, and waste minimization, brought together in 2009 by the United Nations Industrial Development Organization (UNIDO) and the United Nations Environment Programme (UNEP). It integrates the applications of preventive environmental strategies with total productivity and lean manufacturing methods and thereby has become the virtuous process that synergizes and realizes progressive improvements in resource (use) efficiency, waste (generation) minimization, and human well-being (van Berkel 2015). These three goals are indeed sequential and mutually synergistic, as higher resource efficiency realizes and facilitates waste minimization; this reduced waste generation, in turn, realizes and enables well-being; and this higher well-being, in its turn, encourages and enables higher productivity and resource efficiency.

The implementation of resource-efficient and cleaner production is measured in terms of increases in productive output per unit of consumption of materials, water, and energy and in terms of the intensity of generation of waste, effluents, and air emissions per unit of productive output (UNIDO and UNEP 2010). Implementation at enterprise level can be achieved in different ways, most often categorized in eight categories, or prevention practices (Van Berkel 2016), respectively: good housekeeping, input substitution, better process control, equipment modification, technology change, onsite reuse and recycling, production of useful by-product, and product modification. Table 9.1 contains a brief synopsis of each with some generic examples. A systematic assessment based on root source analysis and root cause diagnosis (Van Berkel 2007a) of any particular enterprise or production process leads to the best combination of the above prevention practices. This assessment can follow a traditional plan-do-check-act framework, with different levels of complexity and rigidity.

Manufacturing excellence is at the heart of resource-efficient and cleaner production. It covers the efficiency in using manufacturing inputs (including labor, materials, energy, etc.), the effectiveness in terms of meeting the specified manufacturing outputs (the product, its quality, its timely delivery, and the frequencies of deviations thereof) and the maturity of the monitoring and control systems, and their ability to predict deviations and/or respond thereto (van Berkel 2021). Even though productivity methods like 5S, lean, and Kaizen have been known to the world since 1986, it is repeatedly found that manufacturing firms, particularly micro-, small-, and medium-sized enterprises (MSMEs), remain far from their full and beneficial application (e.g., FICCI 2021). Targeted support for their implementation therefore generally results in impressive resource efficiency and business benefits. This was, for example, evident in the Indian pulp and paper industry (NPC 2023). Emami Paper Mills achieved savings of around USD 45,000 annually by addressing the root causes for high paper rejection (which earlier had to be reprocessed causing extra energy and water use), improving power factor, and reducing downtime for cloth changes on the paper machine. Tirupati Balaji Fibres Ltd. improved workplace management to free up 1390 m^2 floor space and save USD 52,500 annually. It also comprehensively improved machine operations to reduce energy consumption by 41 kWh/ton and increase production capacity by 14%, enabling additional annual sales of USD 1.25 million. Ramji Board and Paper Mill Private Limited improved workplace efficiency which reduced operational costs by USD 42,000 annually and unlocked USD 6800 annual energy savings. Root causes for high paper breakage were reduced by 49–73% on the paper machines, which increased daily production capacity by 25% which will generate additional sales of USD 2.5 million annually.

Further resource efficiency results are possible with the introduction of known best available techniques. This is particularly evident with energy efficiency best practices and techniques, as demonstrated in Coimbatore foundry cluster in India. Coimbatore is home to a flourishing foundry industry serving pumps, automotive, machine, textile, and other engineering industries. Energy costs account on average for 30–35% of manufacturing costs in foundries, with the melting section consuming the lion's share of nearly 70%. Foundries can typically save 5–10% on their energy bill with well-established energy efficiency techniques and better operating practices. UNIDO with the Bureau of Energy Efficiency (BEE) and the Coimbatore Industrial Infrastructure Association (COINDIA) supported the implementation of

Table 9.1 Resource-efficient and cleaner production practices (icons courtesy of UNIDO)

RECP practice	Description	Common examples
	Maintain a clean, organized, and productive (*neat*) workplace to eliminate avoidable *wastage*	• Switch off what is not in use • Repair what is broken or leaking • Keep workplace organized and clean • Minimize and manage inventory
	Choose inputs that are efficient, are effective, and/or pose minimum harm to the environment and health	• Use renewable energy • Use sustainably sourced renewable materials • Use secondary materials, water, and energy • Use less harmful chemical substances (dyes, paints, degreasers, etc.)
	Monitor and control processes and equipment so that these always run at highest efficiency and with lowest wastage	• Establish and follow standard operating procedures (SOP) • Sub-meter use of water, energy, and materials • Install automatic shut-off and overflow prevention valves • Control pressure, speed, temperature, etc. to actual process needs
	Make existing equipment more efficient and less wasteful	• Use energy-efficient motors, fans, boilers, lights, etc. • Close and insulate hot and cold process equipment • Align and debottleneck production lines
	Change over to new technology that is more efficient or produces less waste	• Solar heating, cooling, drying, or lighting • New processes based on green chemistry and/or engineering • Process substitution, e.g., chemical to mechanical
	Use previously *wasted* material, energy, and/or water for similar or alternative purpose in company	• Counter-current or cascaded use of water, energy, and/or materials • Condensate and/or heat recovery • Reuse of incoming packaging for outgoing products

(continued)

Table 9.1 (continued)

RECP practice	Description	Common examples
	Convert a previous *waste* for a useful use elsewhere	• Provide used cooling water for external heating or cooling purposes • Segregate recyclables for external recycling and resource recovery • Industrial symbiosis—reuse of by-products in industrial processes
	Redesign product to reduce its environmental impact during production, use, and/or disposal	• Design for optimal product lifetime • Design for minimum use of water, energy, cleaning, etc. • Design for low-waste manufacturing • Design for refurbishment, recycling, etc.

energy efficiency in micro-, small-, and medium-sized foundries in the Coimbatore region. One hundred thirty foundries implemented 253 measures with a cumulative investment of around USD 3.75 million (Van Berkel 2022). This resulted in energy savings of nearly 1600 tons of oil equivalent, reduced greenhouse gas emissions by more than 15,500 tons, and achieved annual energy cost savings of USD 2.9 million. This was possible with 21 specific techniques, of which 8 typically required an investment of less than USD 2500, 7 required an investment up to USD 12,500, and the remaining 6 needed more than USD 12,500 in investment (UNIDO 2022). One foundry invested USD 55,000 to replace conventional cupola furnace with energy-efficient 12 pulse induction furnace with a payback of 1.6 years only. Another firm installed an efficient shot blast machine costing USD 11,000 for a simple payback of 3.7 years. The replacement of an old motor with energy-efficient motor achieved another foundry a payback of 1.4 years on an initial investment of USD 3500. The addition of variable frequency drive to an existing screw compressor at a cost of USD 3625 achieved a payback in 8 months. Some foundries went further into renewable energy, with one foundry setting up a 1 MWh solar PV plant at a cost of USD 6.2 million with expected payback in 3.2 years.

Business benefits through the adoption of best available techniques and best environmental practices do stretch beyond the energy domain. Four hundred three small- and medium-sized enterprises in Bangladesh, Nepal, and Sri Lanka worked towards resource-efficient supply chains for metal products for the building sector. These implemented a total of 3766 measures, which achieved cumulative annual savings of 33,953 MWh energy, 48,978 m^3 water, and 4434 tons raw materials and avoided annually 13,200 tons CO_2 emissions and 700 tons waste, while unlocking annual savings of EUR 2.9 million (Balakrishnan 2020). Hulas Wire Industries in Nepal, for example, partially replaced hydrochloric acid picking with mechanical descaling, at a cost of just EUR 80, to save EUR 22,500 annually through the reduction of use of hydrochloric acid by 231,000 l annually. Lanka Steel in Sri Lanka connected the roof gutters to an unutilized tank to harvest rainwater, saving annually 2900 m^3 water use with a value of EUR 1330 with an initial outlay of only EUR 30.

Significantly larger environmental and resource conservation benefits are possible with the development and commercialization of new industrial equipment, as, for example, demonstrated by the Facility for Low Carbon Technology Deployment in India. It supports companies and innovators to deploy and validate new equipment designs, using systematic product design and best available simulations, materials, and controls (FLCTD 2023). Shakti Pumps developed a micro-smart positive replacement pump and installed and tested it at 17 commercial, industrial, and service sites. Compared to the conventional single-phase motor pump set, the system performance improved by 40–82%, achieving power savings in the range of 1.31–3.5 MWh annually per system. Promethean Energy developed and demonstrated an advance plate heat exchanger for heat recovery from hot textile dyeing effluent, with advanced Internet of Things controls for process and heat recovery optimization. The demonstration unit at a leading textile manufacturer achieved 98% effectiveness of the plate heat exchanger, reduced the temperature of the dyeing effluent by around 60% (in turn reducing time for effluent treatment), and saved annually the equivalent of 450 tons coal, with an estimated payback within 1 year. Encon Thermal Engineers designed and engineered a regenerative burning system for high-temperature applications in steel and related industries. The factory demonstration unit achieved over 80% heat recovery from flue gases, which contributed to 18% energy savings. The first commercial application in a large industrial reheating furnace confirmed 30+% fuel savings.

9.3.2 Industrial and Urban Symbiosis

Symbiosis occurs in nature where there is a mutually synergistic coexistence and interdependency between two or more different species. The concept has found industrial applications where a previously discarded "waste" from one facility substitutes for a virgin input in another facility. Chertow (2000) defined: "industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity." Comparable terms used elsewhere are regional resource synergies (Van Beers et al. 2007) and eco-industrial parks (Lowe 2001), which though are broader and include the shared use of environmental infrastructure (such as common effluent treatment plants or common waste recycling facilities) and environmental planning and management of industrial estates. A further extension is urban symbiosis, which refers to the use of by-products (wastes) from cities (or urbanized areas) as alternative source of material, water, and/or energy in industrial operations (van Berkel et al. 2009a, b). Similar to industrial symbiosis, urban symbiosis is based on the synergistic opportunity arising from the proximity of urban centers (and associated waste and effluent generation) and potential industrial users through the transfer of physical resources.

Industrial and urban symbiosis have become well established in the Asia-Pacific region since the early 2000s, starting from Japan and Australia and further expanding from there into the Republic of Korea, the PR of China, Thailand, India, Viet Nam, and elsewhere. Waste management and industrial rejuvenation policy were the main initial drivers for industrial and urban symbiosis in Japan, particularly through the Eco-Town program, which was operational between 1996 and 2006 (van Berkel et al. 2009a, b). For example, in the industrial and port city of Kawasaki, symbiotic interactions divert 565,000 tons of waste annually from landfill, substitute 513,000 tons annually of virgin materials, and create business value of approximately 170 MUSD annually (van Berkel et al. 2009a, b). Industrial symbiosis in Australia manifested itself profoundly in heavy industrial areas, particularly the mineral processing zones of Kwinana and Gladstone, initially based on the synergistic use of water, heat, fly ash, and spent catalysts and later expanded to the use of large-volume mineral processing residues in urban development and other non-industrial applications (Van Beers et al. 2007). The Republic of Korea promoted industrial symbiosis as a means for environmental remediation and innovation of its industrial complexes. The industrial complex of Ulsan transformed itself comprehensively and has become a showcase of research and innovation for ecological and commercial benefit through collaboration between different petrochemical, waste management, and allied industries (Behera et al. 2013). Ulsan's 6 km *steam highway*, for example, connects key heat-producing and heat-using industries which each can either draw steam or input excess steam, depending on their fluctuating process demands, which collectively mitigates 146,000 tons CO_2 emissions (Park 2013). Industrial symbiosis also evolved in large petrochemical complexes in the PR of China, for example, the Shanghai Chemical Industry Park, which has 71 enterprises, including 28 major petrochemical and chemical facilities (Yong 2013). Cleaner production and energy efficiency audits resulted in the implementation of 201 resource efficiency measures by 28 companies with an investment cost of 13.2 MUSD and the generation of 30.6 MUSD annual saving. Moreover, collective eco-industrial infrastructures treat and recover effluents (44,000 m^3/day) and select hazardous wastes and supply steam and distilled water from power stations to different industrial users.

The application of symbiosis is not limited to large and resource-intensive industries, as demonstrated in India in select clusters of micro-, small-, and medium-sized enterprises (MSMEs). These clusters comprise comparable industry units within the same or select few industrial sectors and generally have some established forms of collaboration and collective industrial infrastructure, such as a tool room, testing lab, and/or training facilities. This collaboration expanded from the 1990s into the environmental domain with the establishment of collective effluent treatment plants and waste disposal facilities. In select clusters, these have become platforms for symbiotic initiatives at micro- and macro-level. At the micro-level of individual firms, collaborative action focuses on replicable resource-efficient technologies that can be standardized and subsequently procured and installed at multiple units with better cost and operational efficiency. A recent example of such micro-level synergy focuses on select energy-efficient technologies with co-benefits for water and chemical use reduction in the Surat textile processing cluster through, e.g., the installation of programmable logic controls on jet dyeing equipment, use of energy-efficient compressors, and installation of micro-turbines in steam systems for power generation, boiler automation, and condensate recovery (EESL 2023). At the macro-level, firms with identical waste streams are joining forces for collective treatment and recovery. In the Naroda mixed industrial cluster, a spent acid recovery plant has been established to treat spent acid from several dye intermediate manufacturing units for the production of by-product gypsum suitable for cement industry and recovered acid for reuse by manufacturing units (GCPCV 2014). Likewise, several food processing industries have established a common biogas facility to produce renewable energy and recover minerals from their organic waste streams. Informal channels of waste pickers contribute to further symbiosis for common recyclable materials, such as paper, plastics, textiles, and metals (Gokulram 2020). Chertow et al. (2019) studied the Mysuru industrial district with a view to assess the industrial symbiosis potential, defined as the sum of the wastes and by-products from all of the industrial facilities in a defined area that could reasonably serve as resource inputs to other processes. The industrial symbiosis potential calculated based on the analysis of the inputs and outputs of~1000 urban enterprises translates into 84,000 tons of industrial waste, greater than 74,000 tons of CO_2, and 22 million liters per day of wastewater.

Industrial symbiosis is widely promoted as an integral element of eco-industrial parks (EIP). Indeed, a large number of self-declared eco-industrial parks have sprouted up particularly in developing and middle-income countries, most often with an objective of attracting industrial investment. Broadly defined, eco-industrial parks are managed industrial areas that promote cross-industry and community collaboration for common benefits related to economic, social, and environmental performance (World Bank, UNIDO, and GiZ 2021). An international guidance framework is now available, structured in terms of the prerequisite of compliance with national legislation and alignment with international standards and performance areas, particularly park management, environment, economic, and social, leading to a set of 51 key performance indicators (World Bank, UNIDO, and GiZ 2021). A complementary implementation handbook (UNIDO 2017) has been developed and trialed under the Global Eco-Industrial Parks Programme. The handbook currently contains the following tools: EIP assessment tool, EIP selection tool, stakeholder mapping tool, EIP policy support tool, industrial symbiosis identification tool, RECP monitoring tool, and industrial symbiosis opportunities monitoring tool. The EIP assessment tool assesses existing industrial parks against the 51 international performance indicators. It assessed 50 industrial parks across 8 countries: Colombia, Egypt, Indonesia, Nigeria, Peru, South Africa, and Viet Nam (Van Beers et al. 2020). The results showed large differences in performance both between and within countries, with individual parks complying with between 32 and 85% of the key performance indicators. Across all 50 parks assessed, the following topics had the lowest current compliance: energy, local community outreach, environmental and park management and monitoring, waste and material use, and climate change and the natural environment. The complementary industrial symbiosis identification tool supports the identification of by-product synergies and waste exchanges. It was among others successfully applied for three industrial parks in Viet Nam and uncovered nine synergy opportunities (Van Beers et al. 2019). These were protein extraction from fish wastes for production of animal feed, use of alcohol-containing residues from chemical and enzyme companies as carbon source in wastewater treatment plants, use of by-products and off-spec products from fruit processing for animal feed, use of steel slag for cement making, use of kiln slag from steel factory as an alternative raw material for zinc oxide manufacturing, use of ammonium sulfate from steel production for fertilizer productions, use of waste heat from steel plant for steaming and drying at garment factory, waste heat recovery for use in paper mills, and use of zinc slag for production of unburnt bricks.

9.3.3 Wealth from Waste

From an economic angle, any waste is in essence a case of "the wrong resource at the wrong time and/or wrong location" that henceforth warrants disposal. This realization continues to spur interest of businesses, innovators, and communities to create wealth from waste. The waste stream becomes the starting point for a circular manufacturing solution. These might be extensions and incremental improvements on established waste management and recycling technologies and systems or innovations unlocking value retention opportunities and could be part of an industrial and/or urban symbiosis.

Energy recovery from waste is a well-established technology that is widely applied yet equally poses significant risks for environmental burden shifting which speaks to the earlier referred pessimist view on circular economy. Incineration of combustible waste fraction can be a source for the formation and release into ambient air of unintended persistent organic pollutants (POPs), particularly dioxins and furans. Bio-methanation, or anaerobic digestion of organic wastes, produces biogas and a mineral-rich sludge for application as fertilizer or soil improver. Pyrolysis produces a mixture of char and liquid (oil-like) and gaseous fuel. These technologies are well known, yet energy recovery efficiencies remain suboptimal due to poor waste segregation and waste feed preparation and management, suboptimal plant designs, inefficient equipment, and suboptimal process management.

Retaining materials in use is from circularity perspective preferred over energy recovery. A broad distinction is possible between return into the same product, direct reuse into a by-product, and recovery of valuable materials. Direct return of a waste into a by-product happens at handicraft, social enterprise, and industrial scales. Waste fabric is used to stitch unique bags, rugs, and other textiles, for example, by the Rags2Bags in India and alike initiatives. Wood offcuts glued or immersed in resin become a timber substitute for furniture making, as done by, e.g., Hattern in South Korea. Return waste as product is possible through direct reuse or after repair, refurbishment, or remanufacturing, often clubbed together as value retention techniques. Case studies for select products show 80–100% material conservation, 79–99% reduction of greenhouse gases, and 15–80% cost savings through such value retention techniques, compared to manufacturing from virgin materials (IRP 2018). Remanufacturing has been defined as "comprehensive and rigorous industrial process by which a previously sold, leased, used, worn or non-functional product or part is returned to 'like new' of 'better than new' condition, from both a quality and performance perspective, through a controlled, reproducible and sustainable process" (ANSI 2021). In view of persistent consumer preferences for new products and skepticism over quality and functionality of remanufactured products, industry remains reluctant to disclose remanufactured content in products, despite good business opportunity and environmental benefits (e.g., Re:Create 2020). Remanufacturing is though gaining ground and occurring on industrial scale, for example, for common consumables, like printer cartridges, as well as capital goods, such as commercial and heavy earth-moving vehicles. For example, in India, Tata Profile business division remanufactured 33,615 engine long blocks for commercial vehicles during fiscal year 2020, resulting in revenue generation of over 3.5 MUSD, conserving 3760 ton materials, and mitigating 8900 ton GHG emissions (TML 2020).

Recovery of valuable materials through mechanical, chemical, and/or metallurgical processes remains the most common waste to wealth strategy, coving both established paper, metal, glass, and other recycling technologies and material innovations. The latter has turned into a fruitful domain for cleantech innovation and entrepreneurship. Some start-ups are focusing on new applications for previously discarded by-products. One such example is waste banana trees, which are a source of fiber. Saathi Eco-Innovation in India uses waste banana fiber to manufacture renewable and fully biodegradable sanitary pads while also creating new income and livelihoods for farming communities (UNIDO 2018). Anguki Industries in India produces engineering composite materials from waste banana fiber (UNIDO 2023), and Bananatex manufactures fabric and clothing from banana fiber in the Philippines (Fashion for Good 2023). Other start-ups are focusing on the recovery of specific valuable components from select waste streams. Aspartika Biotech extracts valuable omega-3 fatty acids from waste silk pupae for animal feed additive, and Brisel recovers highly dispersed silica from rice husk ash as a valuable filler for rubber tires and products (UNIDO 2018). MiniMines is commercializing an innovative process for highly efficient recovery of high-purity lithium and other valuable metals from Li-ion battery waste (UNIDO 2023). Phool is creating incense from temple flower waste and is commercializing its proprietary process to produce a vegan biomaterial, fleather, to substitute leather (ESP 2023).

Waste to wealth is not limited to solid waste streams. Chakr Innovation removes soot from the exhaust gases of diesel generators and turns this into printing and writing ink (UNIDO 2018). Arvind Mills pioneered the use of 8 million liters per day municipal wastewater for producing process water for its denim-manufacturing unit in Ahmedabad and thereafter established a new business division for industrial water treatment (Arvind 2023).

9.3.4 Green Chemistry and Engineering

Green (or also sustainable) chemistry and engineering comprise high-level sustainability strategies for application in the design of product and process chemistries and of engineering artifacts, particularly industrial plants (Paul and Warner 1998). Whereas environmental chemistry and engineering deal with minimizing the impacts and risks of pollution and waste on the environment, green chemistry and engineering focus on technological approaches to preventing pollution and reducing the consumption of natural resources, particularly non-renewable resources. Neither green chemistry nor green engineering is a separate sub-discipline in their own right, yet rather normative, nature-inspired frameworks in which sub-disciplinary knowledge, methods, and techniques are applied. The application of the twin approaches of green chemistry and engineering has sparked process and product innovations in a range of chemical manufacturing and use sectors, including in the Asia and Pacific (UNIDO 2021).

India is home to diverse ecosystems of cleantech innovators and start-ups using organic—waste—material to manufacture alternative biomaterials to substitute fossil fuel-derived and other harmful materials. Plastic substitution is a focus for such cleantech innovation. TGP Bioplastics produces an alternative for flexible biodegradable packaging made from chemically modified starch (FLCTD 2023). ZeroPlast extracts cellulose from agricultural crop residue and mixes it with bio-based additives and binders to produce a substitute fully compostable alternative for flexible and rigid packaging (FLCTD 2023). Zerocycle produces a seaweed-based bioplastic for food packaging that slows down the fast ripening process of fresh food (UNIDO 2023). Half a dozen firms are involved in manufacturing leather alternatives from different organic materials, including bacterial cellulose grown from coconut water, cork, pineapple fiber, and flower waste (Elle 2023).

Enzyme technology is another application area for green chemistry. Enzymes act as a natural catalyst to increase the efficiency and specificity of chemical reactions, most often at or at near-ambient conditions, avoiding energy-intensive high- or low-temperature and/or high- or low-pressure chemical synthesis. They are already widely used globally, and the pharmaceutical sector would account for half of industrial use in India, with the remainder utilized for detergent, textile, food, pulp and paper, and leather sectors (Chandel et al. 2007). The rapid development in enzyme discovery and production opens new applications either for the development of new and cleaner synthesis pathways for target molecules currently in use, such as for antibiotics in pharmaceutical sector (by, e.g., Cellzyme) (UNIDO 2018), or for nature-inspired alternative target molecules, such as dyestuffs for the textile sector (by, e.g., Demeta) (Demeta 2023).

A complement to green chemistry and engineering is biomimicry, which examines nature and its models, systems, processes, and elements to emulate or take inspiration from in order to solve human and industrial problems. A practical example is hyper-efficient material transfer and mixing in natural systems, replicable in industrial systems. Proburgeon has designed and developed continuous-flow reactors, which have micro-/mini-channel technology and external agitation and packing to improve process performance and improve heat and mass transfer, thus leading to improved productivity and reduction in specific energy consumption, with applications in diverse organic chemical synthesis processes (FLCTD 2023). BluPower mimics a vortex in its low head micro-vortex hydropower turbine for power generation from water flows in irrigation channels, in creeks, and/or even in industrial water systems (UNIDO 2023). Agnisumukh engineered horizontal gas flames with radiant heat transfer, mimicked from charcoal burning, commercialized in India for commercial kitchen, household, and industrial applications achieving on average over 30% fuel savings (UNIDO 2018).

9.4 Scaling the Circular Transformation

Several authors have observed the disconnect between the demand for circular products and services, dominated by consumers and transnational corporations located in the Global North, and development and implementation of circular manufacturing solutions, having to take place in the manufacturing hubs in the Global South (e.g., Hoffstetter et al. 2021). Moreover, the earlier case study on textile and apparel manufacturing (in Box 9.1) found that a grand top-down (re)-design of the current linear economy into a circular economy is unlikely—more realistic appears transformation through bottom-up sprouting of circular innovations by firms in different stages of the global manufacturing value chain that require further support and better coordination. Firms, including non-firm economic actors, such as cooperatives, self-help groups, family enterprises, etc., involved in the manufacturing of goods and delivery of associated services, therefore have the agency for the circular manufacturing transformation. Manufacturing only transforms circularly upon decisive action by firms, regardless of initiatives and efforts of governments, consumers, financial sector, and civil society. This is also reflected in the process model, depicted in Fig. 9.2, highlighting that firms engage with and invest in input activities to pave the way for their circular transformation, particularly entrepreneurship, design thinking, and research and innovation.

Recognizing this critical agency of firms, six key levers or intervention areas are discernable for accelerating the desired circular manufacturing transformation, respectively (as illustrated in Fig. 9.4) (adapted from van Berkel 2023):

1. *Industrial capability:* the organizational and institutional capability of manufacturing firms to plan, operate, monitor, and change, as appropriate, its products, manufacturing processes, business operations, and business models in response to government policy and market developments and making efficient and effective use of—appropriate and applicable—competencies, technology, and financing
2. *Competencies:* the human resource base that operates all functions of the manufacturing firm, covering employer and business operator, particularly in terms of their entrepreneurial competencies, and employees and workforce at

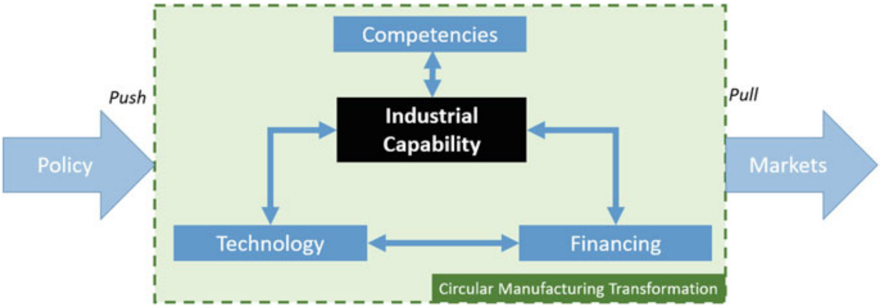


Fig. 9.4 Levers for circular manufacturing transition (Adapted from van Berkel 2023)

large, through their operational, technical, business, analytical, problem-solving, and cooperation skills, craftsmanship, and knowledge

3. *(Appropriate) (clean) technology*: the set of technologies and associated practices that manufacturing firms can utilize for the greening of their manufacturing processes or manufactured goods and their applicability, effectiveness, and affordability within their specific manufacturing and business settings
4. *(Appropriate) financing*: the financing instruments and sources that manufacturing firms can access to finance the implementation of (clean) technologies and environmentally sound products and services and the associated changes in business processes and models and their appropriateness to the specific financing requirements and investment risks of these technologies, products, services, and business processes and models
5. *Government policy*: as a driver, a push factor, for manufacturing firms for their circular transformation, through the coordinated development and predictable and transparent implementation of relevant environment, energy and climate, industry, labor market and skill development, MSME and innovation policy, and strategy and incentive schemes
6. *Markets*: as a driver, a pull factor, through the deliberate use of purchasing power of public and private consumers individually and collectively to preferentially procure and use circular products and services, by domestic and international consumers and trading partners to create a pull factor for firms to adopt inclusive and green practices and techniques

These levers act synergistically. Industrial capability stands central for decision-making and implementation, making effective and efficient use of enablers (or resources), particularly the competencies, technology, and financing, and responding to external drivers, particularly policy and markets. None of these levers is avoidable, yet strengths in one lever can compensate to some extent weaknesses on other levers. For example, strong government policy and regulations can drive some implementation even when industrial capability is, for example, weak. Overall, the scale, speed, and depth of the circular transformation are dependent on the presence, strength, and scale of these six levers.

Following elaborates briefly on the challenges and opportunities under each main lever.

9.4.1 Industrial Capability

The term industrial capability is a shorthand for the firm's internal—organizational, institutional, and systemic—factors and systems that enable the firm to adapt, compete, and succeed in competitive markets and under changing external factors. Firms with higher industrial capability will more easily identify and respond to the need to and opportunities for change and be better equipped to successfully identify, acquire, implement, and deploy new and circular competencies, technologies, business processes, and/or business models. Two partial overlapping dimensions contribute to this industrial capability. First is *manufacturing excellence* or the ability to run manufacturing processes in an industrial manner, meaning with efficiency, replicability, predictability, and quality, under healthy and safe working conditions and in compliance with applicable rules and regulations (van Berkel 2021). Second is *responsible business conduct:* this relates to the willingness and commitment of the firm to consider stakeholders' interests and take responsibility for the impacts of the business on environment and society. This involves taking into consideration market and societal expectations (as, e.g., enshrined in social responsibility standard ISO 26000:2010 (ISO 2010), covering organizational governance, environment, labor practices, human rights, fair operating practices, consumer issues, and community involvement and development. Given these diverse dimensions, the development of industrial capabilities is a multipronged undertaking that improves and innovates many aspects and performances of a manufacturing firm, including, but not limited to, proactive and successful circular transformation.

9.4.2 Competencies

This covers the knowledge, skills, and behaviors of the firm's human resources, including employer, employees, business owner or operator, contractors, service providers, and casual workforce, and their ability and determination (or agency) to deploy these for the benefit of the firm. Better competencies add to industrial capability and enable the firm to continuously adapt and improve, including in terms of its contributions to environment and sustainability.

There are two main entry points. First is *entrepreneurship* or the capacity to organize, manage, and assume the risks of establishing and running an enterprise with the view of making profit. Practicing entrepreneurship, or *enterprising*, is not limited to the manager or owner of an enterprise. Within all roles in enterprises, there is a scope for entrepreneurial behavior in terms of taking own initiative, being kept informed, continuously looking for new opportunities, and taking responsibility for seeing these through to fruition. Second is *skills* which refer to the person's ability to perform readily, repeatedly, and competently any particular task which results from a combination of information/knowledge, training or instruction, and practice or experience. Skills can be specific to the person's role (as, e.g., a welder or painter) or entail the ability to contribute to the work unit's total achievement (regarding, e.g., productivity, quality, and innovation). In view of current industrial trends towards innovation and digitalization, there is growing recognition of the importance of skills for the future, particularly analytical and problem-solving, team working and collaboration, and ability to utilize ICT systems (UNIDO 2019a, b).

Entrepreneurship and skills facilitate circular transformation: firstly, through green entrepreneurship and green skills that are specific and exclusive for an environmental outcome, e.g., establishment and operation of solar rooftop PV systems, eco-tourism, or remanufacturing, and secondly, through including and mainstreaming environmental aspects in all business functions and activities, e.g., employing entrepreneurial competencies to see and realize energy efficiency as a business opportunity or practice waste minimization in performing one's regular tasks as a painter, welder, mechanic, cleaner, or nurse.

9.4.3 (Appropriate) Clean, Resource-Efficient, and Low-Carbon Technology

This concerns the supply of clean technology solutions and green, low-carbon practices that manufacturing firms can deploy. Many technology solutions are already mature, demonstrated, and viable. Others are proven but not convincingly viable, whereas others are in an early stage of conceptualization, innovation, and development. In many cases, clean technologies are hardly known to businesses that could potentially benefit from their application, in particular to MSMEs. Vice versa, the current technology and equipment offer may not meet the specific requirements of firms. There is a need to facilitate matchmaking between demand and supply of clean technology.

9.4.4 (Appropriate) Financing (for Circular Manufacturing)

This concerns meeting the financing needs of manufacturing firms to enable them to invest in inclusive and green business operations and models employing clean and resource-efficient technologies. Financing appears insufficiently available for green investments in manufacturing, due to diverse factors at the side of manufacturing firms (low bankability of firms), at the side of financial institutions (limited consideration of environmental risks and opportunities), and in the financing modalities (mismatch of financing instrument with the earnings model and risk profile of the circular investment).

9.4.5 Government Policy

From a public policy perspective, the circular manufacturing transformation is a crosscutting exercise that traverses a range of policy domains at different levels of government. These include industrial policy (e.g., technology development and innovation; sector growth strategies), SME development policy (e.g., competitiveness, productivity), environmental and energy policy (e.g., pollution control, waste management, energy efficiency, and resource conservation), and regional development policy (e.g., provision of local infrastructures) as well as labor market, employment, and skills development policy (UNEP and GDI 2017). For circular manufacturing, three complementary—and partly overlapping—policy agendas are critical, respectively: environmental policy for industry (UNIDO 2011), sector policy for environmental goods and services sectors, and greening of industry-relevant policy (UNIDO 2016).

A further enabling policy priority lies in the greening of employment policy to ensure a smooth circular manufacturing transformation (ILO 2015). Moreover, the distributional impacts of the circular manufacturing transformation are of concern to policy makers, employers and employees, and communities and society. Complementary policy hence must ensure that the green transformation is a just transition for all stakeholders involved, guaranteeing social security for workers and communities and enabling firms and investors to recover and refocus on new opportunities.

9.4.6 Markets for Inclusive and Green Products and Services

This entails the creation and aggregation of market demand for circular products and services to catalyze implementation and investment by manufacturing and other sectors. Producers in a market economy would follow consumer requirements and preferences. Increased environmental and social awareness and related government policy should sway consumer preferences towards more circular products and services, facilitated by eco-labeling, sustainable public procurement (for government procurement), and voluntary sustainability standards (in global consumer goods supply chains).

9.5 Closing Observation

The circular economy happens when products, materials, and technologies—each a manufactured good on their own—change in terms of their cumulative, life cycle resource footprint to achieve resource circularity, resource efficiency, and/or resource substitution. This circular transformation of manufacturing therefore deserves focus in the circular economy discourse to achieve the reformative aspiration of the circular economy, rather than flipping back and forth between the opposing optimist and pessimist perspectives, both not warranted. Transformation is by definition a process that starts with input activities, here particularly entrepreneurship, systematic design thinking, and innovation, each practiced under a uniting and compelling vision that is circular and thus by default free of any wastage. This is possible as demonstrated by real-time industry examples and experiences, some of which covered here, that deserve mainstreaming and scaling up, by firms and their ecosystems and value chains. The challenge ahead is one of mobilizing and capacitating firms through the suggested levers.

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The Circular Economy, Employment, and Low Carbon in the UK Manufacturing Sector

10

Gev Eduljee

Abstract

Primary legislation relating to the circular economy and to climate change has generally been inherited by the UK prior to its departure from the European Union in January 2020, with the four devolved administrations given the remit for implementation. Post-exit, the UK has enacted domestic legislation in both policy areas. A key target relating to climate change is for the UK to achieve Net Zero greenhouse gas emissions by 2050. No such target exists for the circular economy. The manufacturing sector contributes 11% to the UK's greenhouse gas emission budget, dominated by the chemicals, iron and steel, cement, and food and drink industries. The role of the circular economy in low carbon manufacturing has evolved incrementally, with the *Industrial Decarbonisation Strategy* of 2021 committing to "driving the transition towards a circular economy model" with potential savings of 9 $MtCO_2e$ per annum in industry by 2050, including a reduction in emissions of 3 $MtCO_2e$ relating to UK consumption. Circular economy strategies to lower greenhouse gas emissions have been identified in each of the sectors considered in this paper (automotive, iron and steel, cement, chemicals, and food and drink sub-sectors), the prerequisite being to consider the entire supply and value chain rather than confining circular solutions to the production site. The efficacy of these strategies to reach Net Zero varies, with the iron and steel industry recognised as being particularly challenging, but significant greenhouse gas reductions can nevertheless be achieved in all the sectors considered, relative to technical abatement solutions.

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10.1 Introduction

The United Kingdom (UK) comprises four devolved administrations—England, Scotland, Wales, and Northern Ireland. While the UK was a member of the European Union (EU), key policies and legislation flowed from the European Commission and other legislative bodies in Brussels, though detailed implementation was generally left to Member States and within the UK, to the devolved administrations. Such is the case with circular economy and climate change, the major policies of which the UK inherited prior to leaving the EU. However, Member States had the latitude to adopt more stringent policies than those emanating from the EU, a course that the UK has adopted after leaving the EU on 31 January 2020.

This paper commences with a summary of the UK policy landscape at national and devolved levels, relating to climate change and to the circular economy. The UK manufacturing sector is then discussed in terms of greenhouse gas (GHG) emissions, job creation attributed to circular economy initiatives, and how the latter links with the UK's ambition to achieve Net Zero GHG emissions by 2050. Five industries are examined in more detail—the automotive, cement, food and drink, iron and steel, and chemicals sub-sectors. The paper concludes with reflections on the challenges facing the more widespread adoption of the circular economy in the UK.

10.2 Policy and Legislation

10.2.1 Circular Economy

10.2.1.1 European Legislation

Most European countries have taken their lead from the circular economy policy initiatives of the European Union (EU), and the UK is no exception. A brief exposition of the policy landscape of the EU is therefore in order.

A thematic strategy for sustainable resource use set the scene (European Commission 2005a). The Raw Materials Initiative (European Commission 2008) undertook to "increase resource efficiency and foster substitution of raw materials" and "promote recycling and facilitate the use of secondary raw materials". A resource efficiency roadmap set an ambitious milestone: "by 2020 ... as we move towards a genuinely consumption based, sustainable materials management or a circular economy, where waste becomes a resource, a more efficient use of minerals and metals will result" (European Commission 2011). Recycling and resource recovery from waste plastics leading to more efficient use of fossil fuel is one example. European Commission (2012) called on businesses, labour, and civil society leaders to support resource efficiency and move to a circular economy, explicitly articulated in European Commission (2014a), which set a range of goals and targets forming legislative proposals promoted by Environment Commissioner Janez Potočnik. The impact assessment estimated the creation of more than 180,000 direct jobs in the EU by 2030, in addition to an estimated 400,000 jobs created by the implementation of the waste legislation in force. This would lead to satisfying 10–40% of the raw material demand in the EU, while 62 $MtCO_2e$ of GHG per year would be avoided in 2030 (European Commission 2014b).

The proposals were withdrawn by incoming Commission President Juncker, and substituted with a revised set of proposals referred to as the Circular Economy Package (CEP) and Action Plan "promoting the circular economy across the whole value chain" (European Commission 2015). The CEP mapped out a series of actions with four legislative proposals amending various waste-related Directives, as well as containing targets for landfill, reuse, and recycling, to be met by 2030. The final package received assent from the European Parliament and the Council of Ministers in May 2018 and came into force on 4 July 2018.

In 2019 the European Commission fulfilled a commitment in the CEP Action Plan by presenting the European Green Deal (European Commission 2019). The ultimate goal is for the EU to achieve a reduction of 55% in net greenhouse gas emissions in the EU by 2030 compared to 1990 levels, and to achieve climate neutrality by 2050. In March 2022 the Commission published "a package of [Green Deal] proposals to make sustainable products the norm in the EU, boost circular business models and empower consumers for the green transition" ... proposing "new rules to make almost all physical goods on the EU market more friendly to the environment, circular, and energy efficient throughout their whole lifecycle from the design phase through to daily use, repurposing and end-of-life" (European Commission 2022). The European Green Deal proposes an ambitious package of measures, including strategies for the built environment, for ecodesign of consumer goods, and for textiles, designed "to move to a truly circular economy in the EU".

10.2.1.2 UK National Legislation

With the UK leaving the EU on 31 January 2020, the UK government published its own Circular Economy Package on 30 July 2020, essentially transposing the EU CEP into UK law substantially unchanged, including meeting key targets such as recycling 65% of municipal waste and landfilling no more than 10% of municipal waste by 2035. The UK's CEP aligns with the collective ambition of the UK nations to move towards a circular economy and implementation will ensure that the government maintains and could exceed environmental standards post-departure from the EU. Regulations transposing the 2020 CEP into law in England and Wales came into force on 1 October 2020 (HM Government 2020a).

It may be noted in passing those countries such as China, Japan, South Korea, Germany, and France, relying on the manufacturing sector to a far greater degree, implemented formal circular resource strategies to grow their industrial economies and safeguard their resource base earlier than the UK. China introduced the circular economy concept in its 11th Five Year Plan (2006–2010), and a "circular economy promotion law" in 2008 (Gong et al. 2013). Japan developed an effective circular economy, passing the Law for the Promotion of Efficient Utilisation of Resources in 2000 (Ji et al. 2012). South Korea incorporated energy intensity, resource intensity, and carbon intensity into a so-called Target Management System, adopted in 2012, with 2020 mid-term achievement targets for resource efficiency and productivity (Jin 2016). German resource efficiency policy is based on three pillars: the German National Sustainability Strategy (NSS), the Raw Materials Strategy (RMS), and the Resource Efficiency Programme (ProgRess) (Wilts 2016). Resource productivity has been embedded in the NSS since 2002. In 2012 Germany passed an Act "... to promote Circular Economy and safeguard the environmentally compatible management of waste". France introduced a Bill on energy transition for green growth in 2013, with a chapter on "combat[ing] waste and promote a circular economy: from design of products to their recycling", setting out targets for progressive decoupling of economic growth and use of non-renewable resources.

10.2.1.3 The UK Devolved Administrations

Many of the themes and provisions covered within the CEP relate to the areas of resources and waste policy where the UK nations are already actively involved through existing measures or work underway to take forward commitments made in their respective domestic strategies.

The *Resources and Waste Strategy* (2018) for **England** forms part of the UK government's commitment in the *25 Year Environment Plan* (2018), supported by *The Clean Growth Strategy* (2017), *The Industrial Strategy* (2017), and *The Bioeconomy Strategy* (2018).

The **Welsh Government's** strategy, *Beyond Recycling* (Welsh Government 2021a) sets out its aim of making a circular, low carbon economy in Wales a reality with a set of key actions to deliver the objective of zero waste by 2050. The Welsh Government also identifies the circular economy as a key part of its Economic Action Plan and its Natural Resources Policy. Resource efficiency is also a key component of the legislative framework in Wales included in the "Prosperous Wales" goal under the Well-being of Future Generations (Wales) Act 2015.

The **Scottish Government's** circular economy strategy, *Making Things Last* (Natural Scotland 2016) forms one of the pillars of its manufacturing strategy (Scottish Government 2016). The strategy sets out a vision and priorities for action to move towards a more circular economy, setting a series of ambitious targets to drive circularity. The focus is on supporting repair and reuse, improving non-labour resource efficiency and resource security, and stimulating product re-design for durability and disassembly. In 2019 the Scottish Government consulted on developing further its circular economy legislation. Owing to the COVID-19 pandemic, the presentation of the proposed Circular Economy Bill to the Scottish Parliament was delayed. A further consultation was launched in May 2022.

In **Northern Ireland**, the Department of Agriculture, Environment and Rural Affairs (DAERA) is developing the *Environment Strategy for Northern Ireland*, a draft of which was released for consultation in January 2022. Under Strategic

Environmental Outcome 5 the strategy sets out an ambition for "Zero waste [and a] highly developed circular economy". A Circular Economy Strategic Framework was scheduled for the Autumn of 2022, together with a revised waste management strategy in 2023. A circularity gap report pertaining to Northern Ireland was published in June 2022 (Circle Economy 2022).

10.2.2 Climate Change

10.2.2.1 UK National Legislation

The UK was the first G7 country to legislate a binding national target, contained in the Climate Change Act 2008—to cut UK greenhouse gas (GHG) emissions by at least 80% by 2050 relative to 1990, through investment in energy efficiency and clean energy technologies such as renewables, nuclear, and carbon capture and storage (CCS). Legally binding carbon budgets proposed by the Climate Change Committee (CCC), set up under the Climate Change Act 2008, proposes successive 5-year caps which should not be exceeded if the UK is to meet its emission reduction targets. Six carbon budgets have thus far been set, running from 2008 to 2037. The first and second carbon budgets (2008–2012 and 2013–2017) were met, while the UK is on track to meet the third (2018–2022). However, the UK is not on track to meet the fourth (2023–2027) or the fifth (2028–2032) budgets (Climate Change Committee n.d.). The sixth carbon budget (2033–2037) proposed in 2020 takes into account the revised Net Zero target set by the UK government in 2019 (see below).

As a signatory to the 2015 Conference of the Parties (COP) 21—the Paris Climate Change Agreement—the UK committed to a goal of limiting global temperature increases to well below 2 °C (versus pre-industrial levels) and to pursue efforts towards a 1.5 °C goal. The Climate Change Act 2008 was subsequently amended in 2019, committing the UK to reduce GHG emissions at least 100% of 1990 levels (Net Zero) by 2050 (HM Government 2019). Following advice from the CCC in December 2020, the UK Government adopted its sixth carbon budget in June 2021, which included a target to reduce GHG emissions by 78% by 2035 (HM Government 2021). In 2020 the UK government published an action plan as "one more step on the path to ending the UK's contribution to global emissions once and for all", outlining a ten-point plan across a range of sectors, and other policy initiatives, to achieve Net Zero (BEIS 2020). Pursuant to the action plan, a Net Zero Strategy (NZS) was issued in October 2021, containing policy proposals across multiple sectors. In March 2022 the UK High Court ruled that the NZS was unlawful in part, owing to lack of detail as to how the government will meet its emissions targets. A revision of the NZS was ordered by March 2023.

In addition to the Climate Change Act, the UK has supporting policies and legislation to achieve the objective of Net Zero. Some of these are as follows (Energy and Climate Intelligence Unit Briefing 2021a):

UK Emissions Trading Scheme (UK ETS) Applying to energy-intensive industries (power generation, steel, chemicals, ceramics) the UK scheme follows from its pre-Brexit membership of the European Union Emissions Trading Scheme (EU ETS). Obligated companies receive tradable permits to emit GHG, based on the market price for carbon (HM Government 2020b). Following the amended Climate Change Act 2019, changes have been proposed to the UK ETS, including realigning permits to Net Zero obligations, extending the range of mandated sectors, and adding other GHGs such as methane.

Climate Change Levy (CCL) Save for businesses that are exempt or have a below *de minimis* level of energy usage, companies outside the UK ETS pay a CCL per unit of energy consumption (HM Government 2001). Energy-intensive users can opt out of CCLs if they sign up to a Climate Change Agreement to boost their efficiency. The levy is chargeable on electricity, gas, and solid fuel. Carbon price support (CPS) rates are payable by certain types of businesses and for certain fuels.

Fuel Duty Fuel duty is payable on fuels used in vehicles, for heating and for other uses such as non-road mobile machinery. Fuels subject to the CCL are excluded.

10.2.2.2 The UK Devolved Administrations

While the Climate Change Act 2008 and its amendments applies to the whole of the UK, climate change policy is a devolved responsibility. The devolved administrations have broadly followed UK national legislation, but in some cases set different targets. Supporting mechanisms and financing can also differ (Energy and Climate Intelligence Unit Briefing 2021b).

Scotland accounts for 8.8% of UK emissions. The Climate Change (Scotland) Act 2009 set a target of reducing GHG emissions by 80% in 2050 relative to 1990 (identical to the UK-wide target), with an interim reduction target of 42% by 2020, in addition to annual targets. The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 set a Net Zero target date of 2045. The Act also set an interim target of a 75% reduction in emissions by 2030, relative to 1990 levels of carbon dioxide, methane, and nitrous oxide and 1995 levels of hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride. All of Scotland's statutory targets cover the entire economy. Scotland has introduced The Low Carbon Manufacturing Challenge Fund worth £25 million over 4 years to 31 March 2026, to support innovative low carbon proposals in the manufacturing sector.

Wales accounts for 8% of UK emissions. In 2010 the Welsh government published its Climate Change Strategy, with a target to reduce GHG emissions by 3% each year from 2011 in sectors under the control of the Welsh Government. In 2021 the Welsh government set a Net Zero target for 2050, with interim targets for 2030 and 2040. In 2021 the government published a plan for its second carbon budget, covering 2021–2025 (Welsh Government 2021b).

Northern Ireland accounts for 3.6% of UK emissions. The Northern Ireland Executive's Programme for Government (2008–2011) set a 25% carbon reduction by 2025. In 2019, according to advice from the CCC, Northern Ireland's contribution to the UK's GHG emissions target was to reduce its emissions by 35% on 1990 levels by 2030. However, it was not until 2022 that Northern Ireland's first piece of climate change legislation was passed. The Climate Change Act (Northern Ireland) 2022 set a target for Net Zero emissions by 2050 with interim GHG reduction targets for 2030 and 2040 and a separate reduction target of 46% for methane emissions, which are largely associated with the agricultural sector.

10.2.3 Low Carbon and the Circular Economy

Explicit reference to the circular economy and of its contribution to low carbon manufacturing in the UK has evolved incrementally since the adoption of the Climate Change Act 2008. *Carbon Plan* and *The Carbon Plan* (2011) offered "technical support to businesses and advice to consumers to help promote resource efficiency, increasing business and investor confidence in the transition to a low carbon economy" (Department for Energy and Climate Change 2011a, b). 2017 saw the publication of the government's green paper *Building our Industrial Strategy*, containing brief mention of reducing raw material demand, improving resource productivity, promoting markets for secondary materials, and the promise of more detail in a 25 Year Environment Plan (BEIS 2017a). The white paper *Industrial Strategy: Building a Britain fit for the Future*, also published in 2017, offered under its Grand Challenge 2 (We will maximize the advantages for UK industry from the global shift to clean growth) a commitment to "a regenerative circular economy" and raising the resource productivity of businesses, while the *Clean Growth Strategy* of 2017 contained a commitment to "work towards a zero avoidable waste economy by 2050," and through a Resources and Waste Strategy, "[maximise] resource productivity through more efficient manufacturing processes" (BEIS 2017b). The 25-year plan published in 2018 contained a commitment to improve resource efficiency but made no explicit reference to targets or a circular economy (DEFRA 2018).

As noted above, the Climate Change Act 2008 was amended in 2019 to commit to Net Zero by 2050. Subsequent publications such as the Ten-Point Plan have also been noted in Sect. 10.2.2.1. Perhaps the most explicit reference to the circular economy in the context of low carbon is contained in the *Industrial Decarbonisation Strategy* of 2021 (BEIS 2021). Action 5.5 of the strategy commits to "Support increased resource efficiency and material substitution within industry, by driving the transition towards a circular economy model and increasing reuse, repair and remanufacturing." This action, the strategy notes, could "save 9 $MtCO_2e$ per annum in industry within the UK by 2050, including a reduction in emissions of 3 $MtCO_2e$ relating to UK consumption" (also see below).

In relation to both climate change (Sect. 10.2.2) and the circular economy (Sect. 10.2.3), while the UK has introduced a large number of policies and initiatives, an overarching cohesive policy framework is absent. Referring to climate change policy, this has been picked up by the OECD thus: "The United Kingdom has an elaborate array of policy measures to tackle its emissions of greenhouse gases ... The current report addresses a 'political economy' issue, namely why this combination of measures does not approximate the kind of market-based approach that would be recommended if we lived in a textbook world in which policy was designed efficiently" (OECD 2005). In other words, the UK's disparate policies and legal instruments does not necessarily translate into effective and efficient actions or outcomes.

10.3 GHG Emissions

10.3.1 The Manufacturing Sector

The UK is the ninth largest manufacturing country globally, with an annual output of £183 billion and supporting 2.5 million jobs (MAKE UK 2022). In 2021, the manufacturing sector accounted for 9.7% of total UK economic output (GVA) and for 7.3% of jobs. In terms of GVA the largest manufacturing sectors as a share of total manufacturing are food and drink (17%), transport (14%), chemicals (14%), and metals (10%) (MAKE UK 2022). In 2020 the manufacturing sector contributed 17% to the UK's GDP, in contrast to 73% from the services sector. The sector comprises approximately 270,000 business enterprises, of which 5353 are large enterprises employing 500 or more people.

A breakdown of UK GHG emissions by sector is provided in Table 10.1 (MAKE UK 2020).

The contribution of GHG emissions from activities within the manufacturing sector is given in Table 10.2 (Climate Change Committee 2020; University College London 2021)

"Other manufacturing" includes sectors such as electronics, appliances, machinery, furniture, and packaging. Over 98% of these emissions comprised carbon dioxide, dominated by four sectors: chemicals, iron and steel, cement, and food and drink. Since these sectors require heat for processing materials into products, fuel combustion (mainly fossil fuels) accounted for 86% of manufacturing GHG emissions, with 14% coming from process emissions (UCL 2021). The study notes that much of the reduction in manufacturing GHG emissions since 1990 (57%) owing to efficiency improvements have been taken, with 50% of the change coming

Table 10.1 GHG emissions in the UK by sector (2018)

Sector	Percentage of total GHG emissions
Surface transport	24
Buildings	17
Electricity generation	13
Manufacturing	11
Oil and gas	8
Aviation	8
Agriculture and land use	7
Waste	4
Shipping	3
F-gases	3
Other industry	2

Table 10.2 Breakdown of UK GHG direct emissions from the manufacturing sector (2018)

Sector	Percentage of manufacturing emissions (total 60 $MtCO_2e$)
Other manufacturing	19
Chemicals	18
Iron and steel	17
Cement	13
Food and drink	13
Glass, clay, stone, lime, and plaster	7
Plastic and rubber products	5
Paper	3
Wood	3
Textiles	2

from energy intensity improvements, 25% from fuel switching and 25% from changes in the structure of UK industry, and that "further abatement is not possible without significant disruption to technological production routes" (UCL 2021).

In terms of further reductions, this has a significant bearing on which strategies going forward will bear the greatest fruit—resource-based circular economy solutions, or green energy-based solutions.

10.3.2 The Circular Economy and GHG Emissions

According to one study, circular economy strategies across its entire value chain (production, consumption, and discard) can reduce global carbon dioxide emissions from the cement, steel, plastic, and aluminium sectors by 40% or 3.7 billion tons in 2050. Two principles are invoked: designing out waste (reduce by 0.9 billion tons CO_2 per year) and keeping products and materials in use (reduce by 1.1 billion tons CO_2 per year). Additional interventions such as carbon capture, utilisation and storage (CCUS), and energy substitution would be required to get further GHG emission reductions (Ellen MacArthur Foundation 2019). This is broadly in line with an earlier estimate that the circular economy had the potential to take the European Union three-fifths of the way in mitigating emissions related to the production of material goods (Deloitte 2016).

Following the adoption of the Climate Change Act 2008, a study examined the contribution of resource efficiency to meet the (then) target of 80% GHG reduction by 2050 (WRAP 2009). Four scenarios were modelled: a Reference Scenario, a Quick Win scenario taking into account what can be achieved across all the resource efficiency strategies over 2010–2020 (continuing to 2050 at the same level); a Best Practice scenario using the best currently available technologies and consumption behaviours; and a Beyond Best Practice scenario assuming the maximum potential of the resource efficiency to 2050. Against the Reference Scenario, the Quick Win scenario resulted in GHG emissions saving of 1.8 billion tons by 2050 (4%), compared to the Best Practice scenario of 2.7 billion tons (6%) and the Beyond

Best Practice scenario of 3.5 billion tons (8%) by 2050. For the goods and services sector alone, accounting for 32% of total emissions by 2050, the Quick Win scenario delivered savings of 9% by 2050 compared to 22% (Best Practice) and 28% (Beyond Best Practice) scenarios.

As part of its sixth carbon budget, the UK CCC considered five scenarios for reducing GHG emissions from the manufacturing sector pursuant to meeting a Net Zero target by 2050: resource efficiency (inclusive of circular economy principles); material substitution; energy efficiency; fuel switching; and CCS (Climate Change Committee 2020). Based on a range of scenarios, resource efficiency measures led to an estimated 6–13% reduction in UK industrial emissions in 2050. The report quotes the Energy Transition Commission as "estimating that 40% of emissions from heavy industry can be avoided through circular economy strategies."

For steel, the CCC modelled the sector achieving Net Zero by 2035, mainly through electrification (32%), CCS (29%) and resource efficiency (19%). For the cement and lime sector, Net Zero was modelled to be achieved by 2040, through increased resource efficiency (40%), CCS (23%), bioenergy with CCS (22%) and material substitution (13%). For the chemicals sector, the modelling indicated Net Zero by 2040 through CCS (30%), electrification (26%), hydrogen (24%), energy efficiency (9%), and resource efficiency (5%) (Climate Change Committee 2020; UCL 2021). These sectors are considered in more detail in Sect. 10.5.

This emphasizes the need to tailor low carbon strategies according to the specific characteristics of each manufacturing sub-sector: material resource efficiency/circular economy solutions, while of course desirable, may not achieve the biggest gains. One commentator noted that across the manufacturing sector, 10% of costs were labour, which saw on average a 3% improvement in efficiency per year. Fifty percent of costs were associated with resources such as parts, material, energy, water, and waste, which saw a 1% improvement on average per year. "There is a huge untapped opportunity in [increasing] resource efficiency to 7% per annum, halving total manufacturing resource use within 10 years" (Manufacture 2030 2017). These are essentially circular economy-based solutions. A number of organisations and initiatives at research and pilot scale are active in the UK (Smart Specialisation Hub 2019).

10.4 Job Creation

A study for the European Union found that adoption of a circular economy across the EU-28 had the potential to raise GDP in the EU by almost 0.5% by 2030 compared to the baseline case, together with a net increase in jobs of approximately 700,000 (Cambridge Econometrics 2018). However, of relevance to this paper, the study also found that manufacturing sectors such as food, automotive industry and sales, plastics, and electronics "could lose out" and experience a net loss of jobs.

There have been varying estimates of the number of "new" jobs that can be created if circular economy measures were adopted across the UK economy—it is unclear, for instance, whether the estimates refer to gross or net jobs created. It has

Table 10.3 Circular economy job creation in the UK by 2035

Scenario	New jobs by 2035	Comments
Business as usual	40,000	Mainly in recycling and repair
Growing potential	199,000	Increasing remanufacturing rates to 20% could deliver 120,000 jobs
Transformation	472,000	Increasing remanufacturing by 50% could create 312,000 jobs. Growth in servitisation could increase jobs in rental and leasing by up to 67,000; in recycling by 62,000; and in repair work by 31,000 jobs

been estimated that reuse and remanufacturing create 8–20 jobs and recycling creates 5–10 jobs compared to landfilling (0.1 jobs), all per thousand tons of products (Green Alliance 2014). Remanufacturing also creates twice the employment of traditional manufacturing using virgin resources, since it requires product disassembly and assembly. This has economic implications for the recycling/remanufacturing sector, with these products potentially more costly owing to higher labour costs, and hence also implications in policymaking to encourage markets for recycled materials.

Employment linked to the circular economy has generally been characterized across four categories: recycling, remanufacturing, rental/leasing/servitisation, and repair/reuse. These generally align with five commonly accepted circular business models (Accenture 2014):

- Circular supplies: based on renewable, bio based- or fully recyclable input material
- Resource recovery: recover useful resources/energy out of disposed products
- Product life extension: extend working lifecycle by repair, upgrade, and resale
- Sharing platforms: increase utilisation of products by shared use/access/ownership
- Product as a service: retain ownership to internalize circular resource productivity

One study considered an additional employment category—biorefining (WRAP 2021a). To what extent any of these categories can be assigned to "manufacturing" is open to debate.

A study across the UK economy estimated that for three scenarios (business as usual—no new initiatives; current development rate; and transformation rate) gross job growth to 2030 in the four job categories noted above, amounted to 31,000, 205,000, and 517,000 job, respectively. Net figures were 10,000, 54,000, and 102,000 jobs, respectively (WRAP and Green Alliance 2015).

A follow-up report updated and extended the above study to 2035 (Green Alliance 2021). The modelled results are presented in Table 10.3.

The study estimated new jobs for "Process, plant and machine operatives" to be 87,941 by 2035 under the Transformation scenario.

Table 10.4 UK job creation and GHG reduction from circular economy solutions

Jobs and GHG reduction	No new initiatives	Current development	Transformation scenario
Gross jobs created	36,645	216,173	551,305
Net jobs created	11,441	57,528	98,794
Net reduction in GHG emissions ($MtCO_2e$)	4.3	14.2	33.8

In another follow-up report, it was estimated that between 2014 and 2019 almost 90,000 new jobs were created in the circular economy in the UK. Estimates of job creation and GHG emission reductions to 2030 are presented in Table 10.4 (WRAP 2021a, b, c).

GVA was boosted by £82 billion by 2030. The report concluded that "sectors of the economy which prolong the life of products and materials [i.e., adopting circular economy principles] are already stepping up to this climate challenge, and have the potential to contribute even more in future. They are not the solution to climate change, but they nonetheless have a fundamental role to play in delivering a Net Zero ambition."

A study published by ReLondon estimated that 93,000 circular cores, 15,000 enabling and 122,000 indirect jobs existed in the London area in 2019 (total 231,000 circular jobs). Core circular jobs included reuse and repair, renting and leasing of products, as well as recycling of materials and resources. Enabling circular jobs included jobs in the supply chain of core circular economy businesses such as digital technology or logistics services. Indirect circular jobs included jobs in the supply chain of core circular businesses that indirectly supported their activities, such as government and professional services. Implementing a Transition strategy, the study estimated the creation of 100,000, 20,000, and 163,000 additional jobs, respectively, by 2030 (total circular jobs 515,000) with circular economy businesses contributing potentially a total of £24.2 billion to London's economy by 2030. A breakdown of jobs by sub-sector was provided (ReLondon 2022).

Although not strictly within the remit of this paper, a report by the UK Energy Research Centre estimated that renewable energy and energy efficiency create more jobs per unit of electricity than fossil fuels. Electricity from fossil fuels created 0.1–0.2 gross jobs per GWh of energy generated, solar created 0.4–1.1, wind created 0.05–0.5, and energy efficiency created 0.3–1.0. The study estimated that 10 jobs were created for every £1 million invested in low carbon energy, though it cautioned that "[higher] labour intensity is not necessarily a desirable quality in the long-term" (UK Energy Research Centre 2014). For the construction, manufacturing and installation of various energy systems, another study provided the following data on jobs/MW: (a) Solar PV: 5.76–6.21; (b) Wind: 0.43–2.51; (c) Biomass: 0.4; (d) Coal: 0.27; (e) Gas: 0.25 (Fankhauser et al. 2008). More than 1.2 million are employed in the UK low carbon industry (kMatrix Data Services 2021).

10.5 Circular Economy and Low Carbon Solutions

Five manufacturing industries which have dominated discussion in the UK on GHG emission reduction and, by implication, the circular economy, are the automotive, cement, food and drink, chemicals, and iron and steel sectors, four of which dominate GHG emissions from the sector (see Table 10.2). These sectors are explored in more detail below in terms of the manufacturing process and, in the case of the circular economy, their wider supply and value chains.

10.5.1 The Automotive Sector

As noted in Table 10.1, surface transport is the highest contributor (24%) to the UK's GHG emissions. While this relates principally to on-road emissions, focus has inevitably turned to automobile production—notably, the switch away from fossil fuels towards electric vehicles (EVs) and other low or zero carbon power systems such as hydrogen. The UK Government is committed to phasing out all petrol and diesel cars and vans by 2030, and all petrol and diesel coaches and HGVs by 2040 (Department for Transport 2021).

It has been estimated that with a full transition to EVs, more than 60% of automotive lifecycle emissions will likely come from materials by 2040, shifting the balance of the carbon footprint of cars to materials production (Aldersgate Group 2021). In turn this has focused attention on decarbonising the production process itself through alternative energy choices to implementing circular solutions within the supply and value chain. Circular economy solutions such as reduction in material usage, recycling, and remanufacturing, are all indicated. Reducing the quantity of steel, aluminium, and other materials used in vehicle production has the potential to deliver carbon emission reductions of 8.49 MtCO2e between 2023 and 2032 (Aldersgate Group 2021). If the 575,000 EVs and 1.2 million internal combustion engine vehicles expected to be sold in the UK in 2025 were produced using remanufactured and recycled components, then emissions savings in excess of 40% could be realised, equating to the displacement of 16.9 MtCO_2e in embedded carbon. Favouring remanufacturing over recycling (which often lowers the quality of the material) would further raise this figure (HSSMI 2021). Complex supply chains and long lead times to production means that circular production-based strategies such as designing for disassembly and remanufacture need to be built in at the conception stage. A compelling case for circularity in the automotive sector has been made by the World Economic Forum (World Economic Forum 2022).

European Union Directives and subsequently UK regulations have provided the legislative impetus for recyclability and recycling of end-of-life vehicles (ELV) (European Commission 2000; European Commission 2005b). Under the regulations, vehicle manufacturers must provide a free take-back facility at the end of life, meet annual targets for their brands, currently 95% recovery and 85% recycling by average weight of each ELV. The UK automotive sector has achieved this target since 2015 (SMMT 2021). The regulations are due for review in 2022.

The need to focus on the production process has an increased significance as EVs replace conventional internal combustion engines. It has been noted that production of an EV creates more emissions than the manufacture of a conventional vehicle, mainly due to producing the battery cells: 20–60% of an EV's carbon footprint is generated during production (HSSMI 2021). Carbon reduction strategies include electrification of processes, using low carbon energy sources, adopting and scaling new technologies that reduce process emissions, and an increased use of recycled materials and recycling a greater share of materials (McKinsey Sustainability 2020; HSSMI 2021). Repurposing existing production facilities for EV manufacture, reduces material and energy usage and the amount of waste created which in turn decreases emissions (HSSMI 2021).

Batteries in EVs are carbon-intensive to produce—according to one estimate, about 50% of automotive manufacturing emissions will be attributable to batteries (Aldersgate Group 2021). Coupled with supply issues connected with materials such as cobalt and lithium, effort is being directed towards the potential for reuse and repurposing of batteries—the costs of remanufacturing and reuse have been reported to be approximately 10% of the cost of a new battery (Aldersgate Group 2021). For batteries that no longer meet EV performance standards, alternative conversion options such as performing stationary energy-storage services are being investigated.

Other circular strategies adopted by the sector include mobility-as-a-service business model, coupled with car sharing: privately owned cars are parked 95% of the time (Aldersgate Group 2021). Car sharing/fleet models can dramatically reduce emissions and material costs through optimising use phase and reducing the total number of vehicles in demand.

As part of Jaguar Land Rover's (JLR) Reimagine vision of modern luxury by design, next-generation vehicle models will have floor mats and trims made with ECONYL® fibre from recycled industrial plastic, fabric offcuts from clothing manufacturers, fishing nets from the farming industry, and those abandoned in the ocean. Every 10,000 tons of ECONYL® raw material produced saves 70,000 barrels of crude oil avoids emissions equivalent to 65,100 tons of CO_2e (SMMT 2021). JLR will require all of its global Tier 1 suppliers to apply science-based targets to reduce emissions.

Using 5% of the energy needed to smelt raw aluminium, JLR re-melts scrap aluminium to produce a Land Rover made of 50% recycled aluminium. All surplus metal to the company's supply chain. The car is 428 kg lighter, increasing fuel efficiency. 9.5 kg of recycled plastic is used inside and out, as is sustainably sourced wood and leather. JLR is expanding the use of recycled aluminium in its car bodies through a £2 million REALITY project (Business in the Community 2018).

UK Research and Innovation (UKRI) is funding a project at the University of Birmingham to establish a plant creating a circular economy around the

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magnets and rare metals needed for EVs and renewable technology. The plant will recycle materials from a range of magnet-containing waste streams including EVs, audio products, and hard disk drives (SMMT 2021)

In 2020 Bentley Motors became the first luxury automotive brand to run its in-house logistics on 100% renewable fuels, utilising hydrotreated vegetable oil. Site vehicles are charged with green electricity generated in part by 30,000 on-site solar panels. Compared to conventional fuel, the switch reduces tailpipe CO_2 emissions from logistics vehicles by over 86%, nitrous oxide by up to 30% and particulates by up to 80% (HSSMI 2021).

Caterpillar, manufacturer of construction and mining equipment, operates Cat Reman® a programme providing customers with lower-cost products, shorter downtime and quick, service options. Cat Reman returns products at the end of their serviceable lives to same-as-new condition, reducing operating costs at a much-reduced cost compared to that of a new part. Rebuild programmes increase the lifespan of equipment by providing customers with product updates for a cost far below that of buying a new machine. Rebuild programmes include Cat® Certified Rebuilds, component overhauls at Cat® dealers, Solar Turbines rebuilds, and Progress Rail Services rebuilds. Through the remanufacturing and rebuild process Caterpillar reduces waste, lowers greenhouse gas production and minimises the need for raw materials (Caterpillar n.d.).

10.5.2 Cement and Concrete

UK carbon dioxide emissions from the cement and concrete sector were 7.3 million tons in 2018, 13% of manufacturing sector emissions but 1.5% of the national UK GHG emission budget. Sixty percent of these emissions were from processing activities, 30% from fuel combustion, and the remainder from electricity use and transport (Minerals Products Association and UK Concrete 2020).

As an energy-intensive sector, fuel switching to low/zero carbon options is likely to provide major GHG reduction benefits. However, circular economy solutions also have a part to play. The point has been made that a cross-collaboration between producers, intermediate manufacturers, the construction industry and end users is required to achieve Net Zero for the sector (Hastreiter et al. 2021). Circular economy strategies include:

- **Material substitution**. Clinker is the most carbon-intensive input of cement production. **P**artial substitution of clinker with steel blast furnace slag and coal ash, at levels of 15–25%, would reduce emissions substantially.
- **Fuel substitution**. Primary fossil fuels such as coal and petcoke can be replaced by substitute fuels such as tyres, synthetic fuel made from liquid wastes, and paint residue.

Table 10.5 Cement and concrete: contribution to Net Zero from each technology lever by 2050

GHG reduction strategy	Emissions saving, kg CO_2/t	CO_2 reduction (%)
Indirect emissions from decarbonised electricity. Decarbonising the electricity grid encourages the electrification of the industry	27.05	4
Transport. Decarbonising delivery transport by moving away from petrol and diesel	44.45	7
Low carbon cements and concretes. Innovations in concrete mix design to utilise lower emission constituents, often constituting waste products from other sectors	76.28	12
Fuel switching. The availability of biomass wastes is sufficient to generate over 70% of the heat used for cement production	99.45	16
CCUS. CCUS technologies represent the most significant and technically disruptive investment in the roadmap	390.97	61
Recarbonation. CO_2 absorption from the atmosphere is recognised in UK accounting of greenhouse gases		12
Thermal mass. Carbon and energy savings where heat can be absorbed, stored, and released from heavyweight materials like concrete and masonry, reducing the energy needed to heat and cool buildings		44

- **Demand management**. Emissions from construction and use of buildings can be reduced by managing housing stock better—renovations as opposed to new builds, improved energy efficiency measures, etc.
- **End-of-life management**. This involves reuse and recycling of materials when buildings come to the end of their lives. A comprehensive roadmap based on circular economy/waste hierarchy principles has been developed to aid the construction industry cut waste and maximize value retention of materials (Construction Leadership Council 2020).
- **Thermal mass**. Concrete re-absorbs CO_2 from the surrounding air over its lifetime in buildings through recarbonation. Increasing the exposed surface area of concrete leads to increased CO_2 absorption. Up to 25% of the lifecycle emissions of cement can be reabsorbed through such recycling methods.

Applying the above principles, a roadmap has been developed for the cement and concrete sector to achieve Net Negative (i.e., beyond Net Zero) by 2050, as summarized in Table 10.5 (Minerals Products Association and UK Concrete 2020).

At 61% GHG emission reduction, CCUS is identified in the roadmap as being the principal technology that brings the cement and concrete sector to Net Zero by 2050.

10.5.3 Food and Drink

More properly expressed as the agrifood sector, circular economy, and low carbon strategies in the UK emphasise the need to consider the entire supply and value chain connected to the production, processing, consumption, and post-consumption of food, including activities such as imports of overseas production, and secondary effects such as deforestation. One study estimated GHG emissions associated with UK and overseas primary production as 55.6 and 47.8 $MtCO_2e$, respectively, in 2019. The remaining emissions from the UK food chain are given in Table 10.6 (WRAP 2021b).

> Cement company CEMEX utilises a range of alternative fuels to replace coal and petcoke, including secondary liquid fuels, scrap tyres, paper, packaging and household waste, meat and bone meal, and sewage sludge pellets. Climafuel® is a waste derived fuel which is made using household residual and commercial waste, processed to remove biodegradable matter and produce a solid, clean, and non-hazardous fuel. All recoverable materials are removed for recycling, as a result, significantly reducing waste sent to landfill. The fuel replaces 20–60% of the fossil fuels used at CEMEX's UK cement plants. Secondary liquid fuels (SLF) are prepared from non-recyclable industrial liquid wastes that are landfilled or incinerated without energy recovery. SLF has reduced emissions of sulphur dioxide and oxides of nitrogen by 15% compared to using fossil fuels alone (CEMEX n.d.).

Total GHG emissions in 2019, including emissions outside of the UK, amounted to 158 $MtCO_2e$.

The UK Government has placed considerable emphasis on food security, conservation, decarbonising the food chain and reducing food waste, publishing a comprehensive "farm to fork" food strategy in 2022 (DEFRA 2022a). A ban covering the retailing of all peat and peat-containing products to amateur gardeners in England

Table 10.6 GHG emissions from the UK food chain (excluding primary production)

Stage in the value chain	GHG emissions ($MtCO_2e$) in 2019
UK food and drink manufacturing	9.3
Packaging	5.1
Refrigerant (all UK stages)	3.6
Supply chain transport in UK	6.8
Hospitality and Food Service (catering)	7.9
Retail	5.3
Consumer transport for food shopping	4.6
Transport—home deliveries	0.9
Home (storage and cooking)	9.9
Waste disposal	0.8

and Wales comes into force from 2024. A number of industry-sponsored, government-supported initiatives and campaigns have been introduced—for example, The Food Waste Reduction Roadmap and Toolkit; the Eat Well, Waste Less pilot study; the Love Food Hate Waste Campaign; and The Eatwell Guide. In relation to food labelling, the efficacy of best before, use by, and sell by dates and their influence on purchasing behaviours and on food wastage is being studied. Several large retailers have removed best before dates on their fruit and vegetable lines. Sainsbury's, for instance, estimates this change could prevent the wasting of up to 11,000 tons of food every year, or 17 million individual packages of products (Edie 2022). In June 2022 the Government consulted on a mandatory reporting system for large businesses—those with over 250 employees and a minimum annual turnover—in line with the Food Waste Reduction Roadmap (DEFRA 2022b).

Under a voluntary industry agreement known as the Courtauld Commitment, the UK food and drink sector has committed to a 50% reduction in GHG emissions associated with food and drink consumed in the UK by 2030, against a 2015 baseline. Solutions applying circular economy principles across the value chain have been highlighted, for example, as listed below (Janakiraman 2021; Sage 2022):

- **Food production**. Ensuring that food is cultivated in a way that enhances, rather than degrades the environment—including topsoil regeneration involving recycling farm waste, cover cropping, crop rotation, and mixed farming.
- **Food manufacturing**. Optimising manufacturing processes through better technology, recycling food that would usually be wasted back into the production line, creating new products with leftover by-products and ingredients. Using waste material as an alternative fuel in the manufacturing process.
- **Consumption behaviours**. Designing and marketing healthier food options; encourage less wastage in purchasing habits.
- **Post-manufacture**. Collaborating with downstream stakeholders: redistribute non-sellable food by partnering with food donation enterprises and alternative markets.
- **Recycling animal by-products**. Reclaiming unused meat, bone, and fat for products such as pet food, biofuels such as biodiesel, and soil conditioners.
- **Waste Upcycling**. Using food waste and discarded ingredients and by-products for processing and manufacturing value-added products such as bio-based textiles.
- **Sustainable packaging**. Moving away from single-use plastic packaging, for example, to more environmentally-friendly alternatives; offering alternative packaging-less shopping experiences (buying loose, bring-your-own-container, etc.).
- **Smart systems**. Deploying technologies such as AI and predictive and prescriptive analytics with smart track-and-trace sensors to mitigate food safety issues and minimise wastage.
- **Protective technologies**. For example, applying antimicrobial coatings to reduce and prevent spoilage, contamination and extend the shelf life of food products.

Table 10.7 Pathway to potential 50% GHG reduction in the food and drink sector by 2030

GHG reduction strategies	Percentage reduction (%)
UK agriculture—productivity/carbon storage	3–7
Overseas agriculture—productivity/carbon storage	2–3
Zero tropical deforestation in supply chain	11
Energy decarbonisation and efficiency	13–15
Refrigerant emissions reduction	2
Transport decarbonisation and efficiency	3
Closed loop packaging	0.2
Food waste reduction	2–4
Higher adoption of eatwell guide	9

To articulate the sector commitment to a 50% reduction in GHG emissions by 2030, a roadmap has been developed, as summarized in Table 10.7 (WRAP 2021c).

Particular emphasis has been placed by the Government on plastic packaging, more owing to its polluting potential (marine litter, microplastics, etc.) than to low carbon concerns. In England, retailers must charge consumers a minimum of 10 pence for single-use carrier bags. Since the charge was introduced in 2015, single use plastic carrier bags sold by retailers has declined significantly, from 2.12 billion sold in 2016/17 to 488 million in 2020/21. The number of single use plastic bags sold per person of population has declined from 38 in 2016/17 to 9 in 2020/21 (DEFRA 2022c). Similar legislation is in place in the devolved administrations, all reporting large reductions in plastic bag usage.

Other initiatives targeting packaging include the intended introduction of kerbside Deposit Return Schemes to increase the capture of post-consumption packaging such as plastic bottles (DEFRA 2021; Scottish Government 2020) and a Europe-wide collaborative project across the value chain called CEFLEX, committed to the "collection of all flexible packaging and over 80% of the recycled materials channelled into valuable new markets and applications to substitute virgin materials" (CEFLEX 2022). In 2022 a Plastic Packaging Tax was introduced in the UK at a rate of £200 per ton (HM Revenue and Customs 2022).

Brewing company Adnams collaborate with glassmaker O-I to develop the UK's lightest branded 500 ml glass premium ale bottle, creating carbon savings of more than 1100 tons per annum as well as reducing glass waste by over 1250 tons. Adnams has also brewed beers exclusively for retailer Marks and Spencer using surplus M&S British bread under the name "Used our Loaf."

Beverage company Diageo are removing plastic ring carriers and shrink wrap from multipacks of beer, and are investing to reduce the amount of plastic used in packaging, replacing it with 100% recyclable and biodegradable cardboard.

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Budweiser Brewing Group UK&I concluded a 15-year power purchase agreement with the UK-based renewable energy developer Lightsource BP that will provide 100% of the purchased electricity for Budweiser's two main UK breweries. The company has a global commitment to secure 100% of all of their purchased electricity from renewable sources by 2025.
Source: British Beer and Pub Association (2019)

10.5.4 Steel

The UK produced 5.8 million tons of iron and 7.2 million tons of crude steel in 2021, employing 16,680 people principally at six sites. Since most of the pig iron goes into steelmaking, this section focuses on the steel industry. Over 75% of UK steelmaking capacity is located at two sites at Port Talbot and Scunthorpe, using the Blast Furnace and Basic Oxygen Furnace (BF-BOF) method whereby steel is made from iron ore, accounting for 81% of UK steel. The remaining four sites deploy the Electric Arc Furnace (EAF) method utilising scrap steel and electricity. The latter is less emissions-intensive, avoiding the need for 1400 kg of iron ore, 740 kg of coking coal, and 120 kg of limestone. Energy requirements are reduced by 40% and GHG emissions are reduced by 60% relative to the BF-BOF process (University College London 2021). GHG emissions from basic iron and steel manufacturing in the UK amounted to approximately 11.4 $MtCO_2e$ in 2020, about 17% of emissions from the manufacturing sector, or around 2% of total UK emissions (University College London 2021; Stats Wales 2022).

The CCC has recommended that steelmaking reaches Net Zero emissions by 2035 (UK Parliament 2022). The Committee's Balanced Net Zero Pathway scenario identifies the following principal means from a baseline of 11.5 $MtCO_2e$, with 0.6 $MtCO_2e$ emissions remaining (Climate Change Committee 2020):

- Electrification: 3.7 $MtCO_2e$ (32%)
- CCS: 3.3 $MtCO_2e$ (29%)
- Resource efficiency: 2.2 $MtCO_2e$ (19%)
- Energy efficiency: 0.7 $MtCO_2e$ (6%)
- Hydrogen used in EAFs, producing Direct Reduced Iron (DRI): 0.6 $MtCO_2e$ (5%)

Since steelmaking, and in particular the EAF process, is energy intensive, renewable energy sources will be key to the production of both electricity and hydrogen/syngas. Retrofitting CCS is also challenging, requiring significant capital (BEIS 2021).

In terms of the circular economy, solutions need to be extended across the entire supply and value chain to be effective (SteelConstruction.info n.d.):

- **Utilising by-products**. Steelmaking produces on average 200 kg (EAF) to 400 kg (BF-BOF) per tonne of steel as by-products, comprising slags (90%) and dusts and sludges (10%). Utilisation rates for slag are typically high, between 80–100%, as raw material substitution in cement, fertilisers, and asphalt. Process dust can be processed to recover zinc and iron. Process gases can be used to generate steam and electricity for on-site use, or for export.
- **Reuse and recycling**. A survey in 2013 indicated that in the UK recycling rates of in-use steel was high, ranging from 98% for rebars in concrete superstructures, to 93% for heavy structural section and light structural steel to 71% for steel piles (average 91%). Reuse varied from 15% for sheet piles to 10% for steel cladding to 0% for internal light steel (average 5%).
- **Utilising scrap steel**. Scrap steel derives from steel production (20%), metal fabrication (30%), and end-of-life activities such as demolition and product discard (50%). As noted above, utilising scrap in steelmaking can significantly reduce GHG emissions connected with the manufacturing process. However, of the 11.3 MT of steel scrap produced annually in the UK, only 2.7 MT is used internally, with the rest exported. Re-shoring this exported scrap will provide significant benefits in terms of achieving GHG emission reductions.

In summary, the CCC recognises the steel sector as posing a particular challenge to Net Zero ambitions, owing to complex supporting infrastructure (for example, production of hydrogen/syngas for DRI processing, and retrofitting of CCS) and high investment costs, for example, building new EAFs to utilise scrap steel (Environmental Audit Committee 2022). Circular economy solutions have their part of play, notably in downstream sectors such as construction, and in recycling and reuse activities.

While more than 85% of the structural steel in existing buildings in the UK is recycled at the end of their service life, less than 15% is reused. Undertaken at the University of Birmingham, the Reuse of Structural sTeel in cOnstRuction project (RESTOR) is the first project of its kind to apply sophisticated non-destructive testing (NDT), machine learning optimisation, and building information modelling to reuse structural steel in construction. RESTOR will optimise the repurposing of used steel members and validate their structural performance during their second lifespan. The outputs of RESTOR will therefore enable sustainable delivery of the infrastructure projects planned as part of the post-COVID-19 economic recovery strategy (Engineering and Physical Sciences Research Council 2022)

10.5.5 Chemicals

In 2019 GHG emissions from the chemicals sector amounted to 11.4 $MtCO_2e$, 18% of total manufacturing emissions and 2.2% of total UK direct GHG emissions (Climate Change Committee 2020; University College London 2021).

Approximately half of UK chemicals emissions derived from energy usage, and half from feedstocks. The sector is highly diverse, comprising petrochemicals, polymers, basic inorganics, speciality chemicals, and consumer chemicals as its main products. The sector employs 99,000 people across approximately 75 large companies and 2500 SMEs and micro-enterprises. In 2016 the sector contributed £11.3 billion or 6.6% of total UK manufacturing GVA and 1% of GDP (BEIS 2017c). The sector is characterised by interdependencies between upstream and downstream producers, resulting in clustering of operations with co-located operations and pipeline connections, permitting the exchange of products and by-products.

Taking 2018 as the base year, member companies of the Chemical Industries Association, the sector's UK trade body, have committed to halving CO_2 emissions by 2034 and by 90% by 2050. This is generally in line with the analysis conducted by the CCC in relation to the UK's sixth carbon budget, with a Balanced Net Zero Pathway (BNZP) indicating a ca. 50% emission reduction pathway by 2034 for the sector with 6% residual emissions by 2050 (Chemical Industries Association 2020; Climate Change Committee 2020).

In terms of energy usage, the chemicals sector sits between energy-intensive and non-energy-intensive industrial sectors (Griffin et al. 2018). With some 85% of GHG emissions deriving from energy use and 15% from process emissions, GHG emission reduction strategies for the chemicals sector have tended to focus on large scale decarbonisation technologies such as CCS, CCUS, decarbonisation of the electricity grid, etc., with other solutions such as energy and resource efficiency playing a smaller though still significant part in terms of reaching Net Zero by 2050. Taking a baseline of 11.4 $MTCO_2e$, the CCC modelled the following reductions associated with a BNZP (Climate Change Committee 2020):

- CCS: 3.4 $MtCO_2e$ (30%)
- Electrification: 2.9 $MtCO_2e$ (25%)
- Hydrogen: 2.7 $MtCO_2e$ (24%)
- Energy efficiency: 1.0 $MtCO_2e$ (9%)
- Resource efficiency: 0.6 $MtCO_2e$ (5%)
- Remaining emissions: 0.7$MtCO_2e$ (6%)

According to the CCC's modelling, the majority (~80%) of the chemical industry's direct emission reductions will require access to a small number of key technologies such as CCS and hydrogen production along with decarbonisation of the electricity grid (Griffin et al. 2018). This also points to the advantages of clustering and co-location, where economies of scale and symbiotic exchange of energy and products is possible. As an example, the sector reports that since 1990 its energy efficiency has improved by 35%, through investment in alternative power generation such as co- or near-located combined heat and power (CHP), which supplies a third of the sector's power needs (Chemical Industries Association 2020).

Notwithstanding the dominance of decarbonisation technologies, the CCC noted that "complementary actions such as building on the sector's energy efficiency progress, enabling circularity and embracing all other possible adaptation measures, will continue to play their significant parts in the collective effort needed in mitigating climate change." University College London (2021) states that "an important means of reducing emissions is to make the chemicals sector more circular (for example, through re-use, remanufacture and recycling), thereby lowering the requirements for new production ... reduc[ing] production costs, create[ing] new opportunities in, for example, recycling businesses, in addition to reducing environmental impacts including carbon emissions." Circular economy strategies identified include the following:

- Better design, increasing product longevity, reducing product demand
- Chemical recycling, e.g., plastics into fuels
- Feedstock substitution, e.g., methanol production from biomass
- Green energy, e.g., production of ammonia using renewable energy.

Another study identified the following "top five" circular economy strategies for the chemicals sector (Elsevier 2019):

- Source raw materials from safe and renewable points of origin
- Treat internal manufacturing pipelines as sources of reusable material
- Refurbish asset parts and machinery rather than discarding them
- Form trade partnerships to exchange waste products for renewable resources
- Make safety and regulatory compliance core components of company culture.

This chimes with another study (Systemiq and Center for Global Commons 2022). The report acknowledges that presently the global chemical value chain is predominantly linear, with low reuse and recycling rates and significant waste generation. Demand-side circular economy approaches will be needed to reduce the reliance on technological solutions that are still scaling up, such as CCUS, and to reduce the growth of upstream and downstream waste and product discards. Applying circular economy approaches can reduce total demand in the global system by 23–31% relative to the present linear system, with elimination representing 41% of total circularity impact, reuse 19%, substitution 14%, and recycling 26%. Reducing future chemical production can reduce the global transition investment needed by over USD 1 trillion (ca. 30% of total incremental investment required) between 2020 and 2050.

Significant research effort is being applied to further circular economy uptake. For example, UK Research & Innovation (UKRI) has created the National Interdisciplinary Centre for the Circular Chemical Economy (CircularChem) "[bringing] together stakeholders from academia, industry, government, NGOs and general public to transform the UK's chemical industry into a fossil-independent, climate-positive and environmentally-friendly circular economy" (CircularChem n.d.). The Centre aims to invest £30 million on projects in the themes *Enabling Technologies for Circular Chemical Economy* projects (biothermal, hydrogenolysis, electrochemical) and *Process Integration and Whole System Optimisation* (process integration, life cycle assessment, social justice).

In June 2022 Tata Chemicals Europe (TCE) opened the UK's first industrial scale carbon capture and usage plant. The £20 million investment captures 40,000 tons of carbon dioxide each year. In a world-first, carbon dioxide captured from energy generation emissions is being purified to food and pharmaceutical grade and used as a raw material in the manufacture of sodium bicarbonate which will be known as Ecokarb® and will be exported to over 60 countries. Much of the sodium bicarbonate exported will be used in haemodialysis to treat people living with kidney disease. The project will see TCE make net zero sodium bicarbonate and one of the lowest carbon footprint sodium carbonate products in the world (Tata Chemicals Europe 2022)

In 2022 INEOS Oxide launched a new certified Bio-Attributed Ethylene Oxide (EO), produced by completely substituting fossil feedstock with renewable biomass. The material delivers a GHG saving of over 100% compared to conventionally produced EO. EO is an important building block for a wide variety of derivative products, which are used in the production of detergents, thickeners, solvents, and plastics. EO is consumed internally by INEOS Oxide in the production of intermediates such as glycols, ethanolamines, glycol ethers, and ethoxylates (INEOS Oxide 2022)

The UKRI Industrial Strategy Challenge research fund is providing £20 million to support four innovative recycling plants, projects which will undertake chemical recycling methods to turn end-of-life plastics into chemicals that can be used to produce virgin grade plastics as well as bitumen-type residues for laying roads. Chemical recycling combined with low-carbon energy inputs, for example via hydrogen, can reduce emissions of a ton of plastic by 91% compared to current fossil production. Taken together, mechanical and chemical recycling process could lead to plastic recirculation rates of 62%, not far off 85% for steel and 70% for aluminium (UKRI 2020).

10.6 Conclusions

The circular economy is firmly embedded in UK policymaking and is acknowledged as a corrective to the take-make-dispose model that dominates its and the global economy. Companies are adopting circular business models, for example providing servitisation as opposed to outright purchase, especially to retain high embedded value of materials within their products, as the example of Caterpillar in Sect. 10.5.1 illustrates. This has fed into sector-wide circular economy solutions, for example, of leasing in the automotive industry, or the return, repair/renovation and resale/leasing of mobile and smartphones. At a cross-sectoral scale examples noted above include the use of waste plastics in automotive manufacture, and waste materials as substrates for alternative fuels.

Nevertheless, while many examples of circular practices can be identified at a company or sectoral level, much remains to be done for the UK to become truly circular. Indeed, the question as to how circular the UK is, has not been definitively resolved. The UK measures raw material consumption and resource productivity, but as tracking indicators rather than in a policy/improvement target context. Detailed material flow data within the economy are lacking. Other resource efficiency metrics relevant to measuring circularity at different scales and across different sectors have not been formalised, nor an agreed methodology.

Furthermore, in sectors that rely on public-facing business transactions, the central role of the consumer and sustainable consumption is often underplayed in discussions concerning the introduction of circular models such as leasing, repair, and reuse. Sustainable consumption goes hand in hand with sustainable and efficient use of resources, but it remains the least studied aspect of the circular economy, and decidedly more difficult to tackle because it is more behavioural than technological. Social pressures influence behaviours relating to purchase and retention of products—even if a product was designed for longevity, changing fashion may still consign it to the disposal bin.

In terms of policymaking, the essence of the circular economy concept is that it should drive a balanced set of policy instruments on both the supply (waste) and demand (production) side of the economic cycle. Circular economy policy has thus far focused overwhelmingly on the waste management cycle. This exposes a particular vulnerability of the circular economy: the inter-connectedness of the production economy with the management of waste and of secondary resources. Because a viable business model for the creation of secondary materials relies on reliable and predictable offtake markets, any weakness in the latter will impact the entire management chain, down to the collection of these materials as a discard. Hence the emphasis commentators have placed on the development of so-called "pull" measures to help build resilient markets for these additional secondary materials, balancing out the "push" measures such as high recycling targets and landfill bans. Concentrating on the latter to the exclusion of the former will merely destabilise the circular economy.

In terms of GHG emission reductions, circular economy/resource efficiency principles have been recognised as providing effective solutions, but the quantum of these reductions will vary according to the structure and characteristics of individual sectors. More to the point, circular economy solutions must address and encompass the entire supply and value chain, rather than focusing solely on the manufacturing entity, if low carbon outcomes are to be maximised.

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Circular Economy through Technology for Waste-to-Energy

11

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Abstract

The amount of waste, which is produced by a citizen, is directly related to economic growth and prosperity. Even though we target for circular economy waste treatment and waste to energy are still essential today. The reduction of the amount of waste and its toxicity decreases the impact on the environment. The avoidance of the release of methane as climate-wrecking gas during landfilling and dumping has to be mentioned as well. In the future carbon capture and storage at waste to energy plant may play a role to prevent CO_2 emission further and to capture CO_2 from biogenic sources as well. This study presents the details related to waste dump and landfill, incineration processes and technologies, thermal processes used for organic substance degradation, plant technology, design references, and project development and a few case studies in Indonesia, India, and Germany.

Keywords

Municipal waste · Waste-to-energy · Technology · Case studies · Energy efficiency

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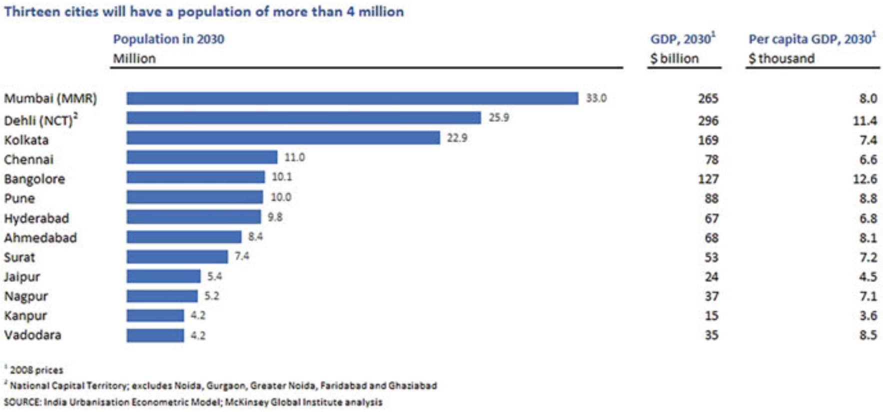


Fig. 11.1 Urban growth in India (The Economist 2017)

11.1 Overview

11.1.1 Introduction

Waste-to-Energy (WtE) is still an underdetermined chapter of power generation in India. Although there are a couple of good reasons like protection of the environment (especially protection of soil and groundwater) and use of the energy content, large-scale waste-to-energy plants are quite rare on the continent.

Today Indians produce 0.4 kg waste per capita and day as an average,[1] which is low compared to the world average of 1.2 and OECD countries of 2.2.[2] But with increasing urbanization and development the waste generation will increase. In Fig. 11.1 the growth of Indian mega-cities to 2030 is shown, which will boost the already high waste generation in India (see Fig. 11.2). The growth of "smaller" cities will happen, too. People living in urban environment have a different way of nutrition and produce more and different waste. These effects will tremendously change the waste situation in India.

The main reason to focus on waste handling, management, and treatment is protection of the environment.

[1] State of the 3Rs in Asia and the Pacific, UN Center of Regional Development, 2017.

[2] What a waste: a global review of solid waste management, Urban Development Series Knowledge Papers, World Bank, 2012.

Fig. 11.2 Top municipal waste generating cities in India 2016 (Solid Waste Management in India, ICRIER, Utkarsh Patel, 2019)

11.1.2 Circular Economy

India has many resources, but these are finally limited. Therefore aspects like recycling, urban mining, and energy utilization will become more and more important, even in Indian countries. Waste management is integrated in an overall system called circular economy (see Fig. 11.3), which covers the aspects mentioned before. The general idea is to use, maintain, and refurbish material, goods, components, etc. as long as possible. If this is no longer possible, all waste, in this case all biological and technical materials should be recycled as far as possible. Nevertheless, part of the waste or material stream has to be diverted for treatment and final disposal.

Figure 11.3 shows the three main methods of waste treatment:

1. Anaerobic digestion and composting
2. Thermal treatment
3. Landfilling

Focus of this paper is on thermal treatment, especially incineration and landfill of waste.

Once a collection system is introduced, different processes from recycling to landfilling up to incineration are suitable. All of these processes can be done in an environmentally friendly way. All elements of the circular economy have an underlying social dimension besides all the technologies we deal with. As mentioned before, any changes of living standards and condition influence the circular economy and subsequently the waste management and vice versa.

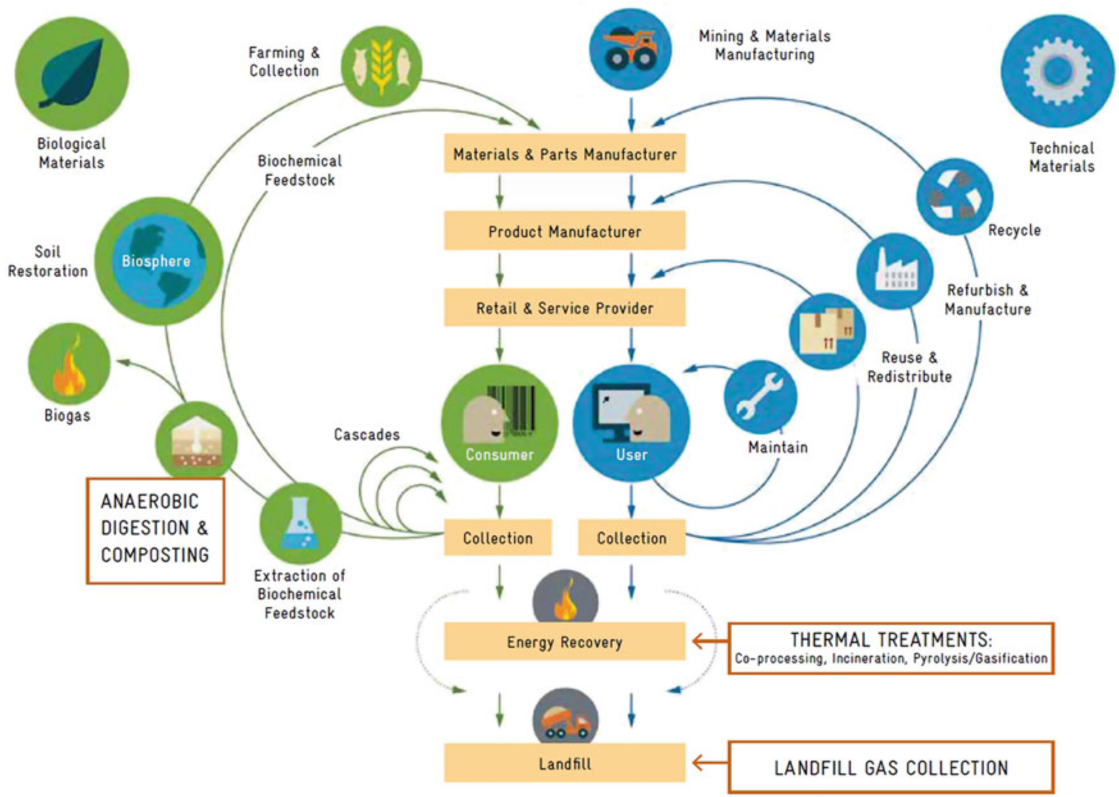


Fig. 11.3 Circular economy (waste-to-energy options in municipal solid waste management—a guide for decision makers in developing and emerging countries, published by GIZ (2017))

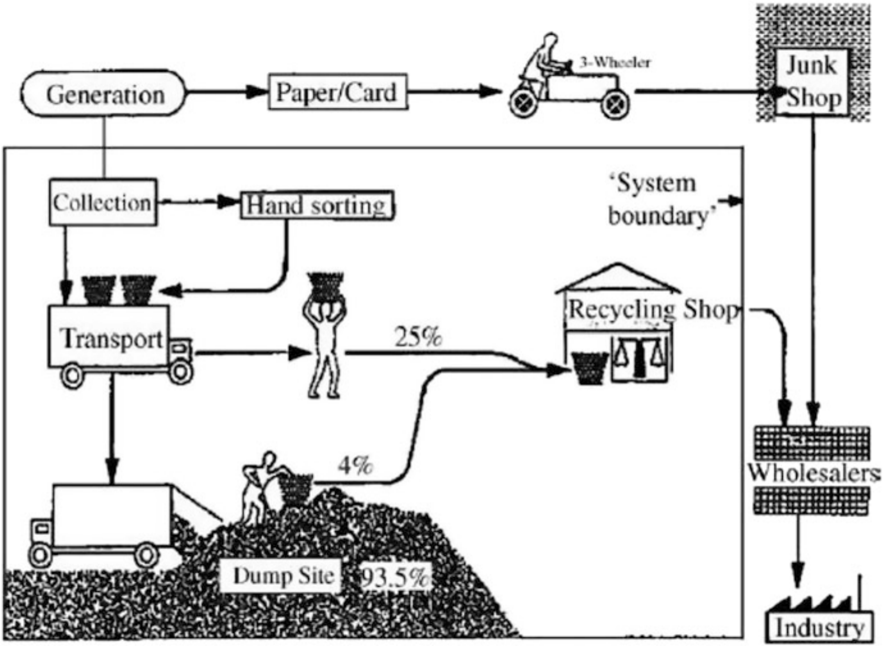


Fig. 11.4 Informal recycling system (achievement of sustainable solid waste management in developing countries Lindell 2012)

Owing to poverty and the availability of cheap and marginal employment informal recycling has been established in the chain of waste collection and dumping (see Fig. 11.4). This form of recycling can be called scavenging, but it is the income basis of the poorest of urban population in developing countries. Every change due to industrialization or improvement of the waste management system will have a social impact, which needs to be taken into account.

11.1.3 Waste Composition

For the following discussion it is necessary to broadly categorize the composition of household or domestic waste. The view on Fig. 11.5 shows the difference of waste from Indian and OECD countries.

In India organic compounds are as high as 57%, whereas in OECD countries the portion is around the half. This has a strong impact, e.g. the heating value and other properties of the waste (see also Table 11.1).

One challenge for incineration in developing countries is achieving the minimum heating value of around 7.5 MJ/kg required for a self-sustaining combustion. The influence of separation of resources by upfront sorting and the big impact of organics and plastics on the heating value are shown in Fig. 11.6.

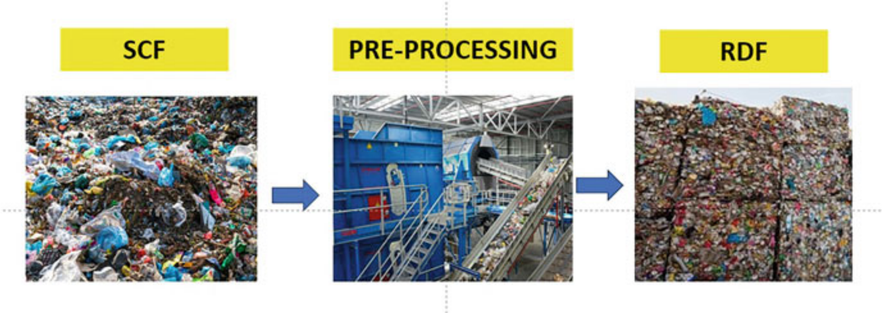


Fig. 11.5 Waste composition in Indian and OECD countries (what a waste: a global review of solid waste management, urban development series knowledge papers, World Bank, 2012)

Table 11.1 Various waste analysis (VDI 3460 emission control—thermal waste treatment—fundamentals, 2014)

	NCV (MJ/kg)	Ash (%)	H_2O (%)	LOI (%)	*S* (%)	Cl (%)
Household waste OECD range	7–15	15–35	15–35	40–60	0.2–0.5	0.4–1.0
Household waste German sample	9.4	25.3	32.6	/	0.2	0.5
Household waste developing countries	2.6–7.6	17	72	/	0.2	0.5
RDF	15	12.7	27	/	0.2	0.4
Sewage sludge	7.7	53	15	/	/	/
Waste wood	15.9	3.9	11.5	/	0.04	0.1

The influence of income and living environment is illustrated in Fig. 11.7. There is shown the waste composition and amount per capita of various cities all over the world.

The higher portion of organics in the developing countries is clear in the table above. Conversely, the higher waste production in the OECD countries (given is the example of Paris) is clearly proved. Please note that the average waste production of an Indian citizen of 0.7 kg/day (noted in the introduction) equals to 256 kg/year.

11.2 Waste Dump and Landfill

After collection, waste is usually dumped in India, which means to put it on an empty area (see Picture 11.1). Without any protection systems, the waste dumps will harm the environment by littering, leakage of polluted water, and uncontrolled spontaneous fires caused by accumulated methane. In general, dumps and landfills also

Fig. 11.6 Influence of the extraction of resources on the heating value

Fig. 11.7 Composition of household waste per capita (kg/capita/year) in various cities of the world (waste-to-energy options in municipal solid waste management—a guide for decision makers in developing and emerging countries, published by GIZ (2017))

consume space, which might not be generally a problem in rural India but is a serious one in the cities.

Modern landfills have an effective sealing system to prevent leakage, are managed and compacted, and covered after usage (see Fig. 11.8). Doing landfilling allows using of landfill gas to produce electricity in gas engines. The landfill gas is the product of aerobic and anaerobic degradation processes in the landfill body,

Picture 11.1 Waste dump in Ghazipur

which is produced anyway and harms the atmosphere as greenhouse gas if it is not combusted and used for energy. The generation capacity is in the low MW range.

11.3 Incineration

11.3.1 Introduction

Another major reason for the development of waste incineration plants was the risk of diseases caused and transmitted by lack of hygiene (e.g. cholera epidemics at the end of the nineteenth century). Due to these reasons the first Waste-to-Energy (WtE) was built at the end of the nineteenth century in London and Hamburg (see Picture 11.2).

Waste incineration has been continuously developed over the last century. Meanwhile waste incineration is a mature and proven technology. Iqony is an owner, engineer, and operator of WtE plants since the early eighties of the last century.

The main reason for incineration is to reduce the amount of waste and to reduce the amount of pollutants released to the environment. One of the first Waste-to-Energy (WtE) plants was built at the end of the nineteenth century in Hamburg (see Picture 11.2) due to these reasons.

Fig. 11.8 Modern landfill sealing system (Landfilling of waste, Pasel, Reich, 2000)

11.3.2 Chemical Reactions During MSW Incineration

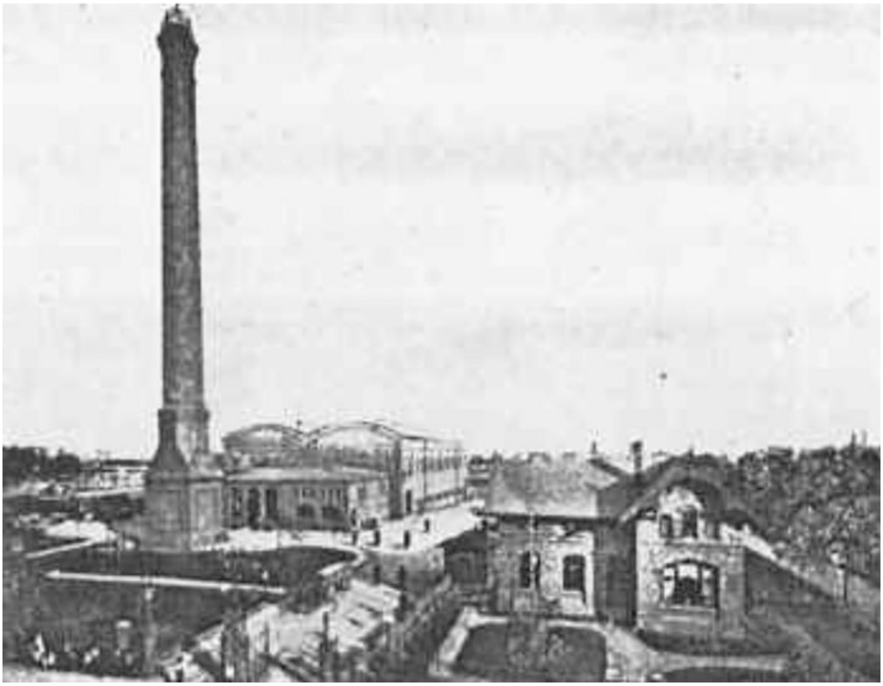
Basic knowledge of chemical process occurring and of the resulting mass flows is necessary to understand the processes in a municipal solid waste incineration (MSWI) plant and to be able to assess appropriate environmentally protective measures. Table 11.1 shows data characterizing the fuel properties of municipal solid waste (MSW) compared to conventional fuels.

Table 11.2 indicates that MSW differs significantly from conventional fuels. Most times, the calorific value is lower, while the ash content is higher. With respect to the calorific value, MSW and brown coal are most similar.

Table 11.3 shows the medium chemical composition of MSW and the most important chemical reactions of the constituents during incineration process.

From a chemical view, combustibles in MSW, as those of other solid fuels, consist of a complex mixture of hydrocarbons being degraded (i.e. combusted) by oxygen at high temperatures. Oxygen may be provided most simply by combustion air.

Carbon (C) reacts with oxygen from combustion air to carbon dioxide (CO_2), hydrogen reacts to form water. These oxidation reactions are the main reactions of an incineration process. In case of incomplete incineration, toxic carbon monoxide (CO) is generated instead of carbon dioxide. Sulfur present in combustible compounds is mainly converted to sulfur dioxide (SO_2), nitrogen is transferred to nitrogen oxides (NO_x) or molecular nitrogen (N_2). Water contained in waste evaporates. In most common process conditions, these reaction products are gaseous and pass into the flue gas. Main components of flue gas are inert nitrogen from combustion air and unburnt excess air.



Picture 11.2 First German WtE Plant in Hamburg (1896) (MVR Müllverwertung Rugenberger Damm GmbH & Co. KG)

Table 11.2 Characteristic data of MSW compared to conventional fuels

Fuel	Water content (weight %)	Combustibles (weight %)	Ash content (weight %)	Calorific value (kJ/kg)
MSW	25–28	39–49	26–33	8000–9000
Wood (air-dry)	12–25	74–88	0.2–0.8	15,000
Peat (air-dry)	20–35	56–79	0.4–9.0	15,000
Brown coal (soft)	40–60	34–58	2–6	8500
Gas flame coal	1–10	77–96	3–13	27,000

At high combustion chamber temperatures, non-combustible mineral constituents of waste mostly undergo solid–solid reactions. Sintering processes lead to partial caking. The end-product of solid incineration is called ash.

Halogens contained in waste, chlorine and fluorine, react to a large extent to produce HCl and HF which are transferred to the flue gas. Among the heavy metals, mercury evaporates mainly in elemental form. Besides, mercury is partially transformed to the metal chloride, as are many other heavy metals. The metal

Table 11.3 Medium chemical composition of MSW and important chemical reactions during incineration process

Group	Element/ compound	Medium content (weight %)	Main reactions	Main output flows
Combustible elements	Carbon C	23	$C + O_2 \rightarrow CO_2$ $C + 1/2\ O_2 \rightarrow CO$	Flue gas
	Hydrogen H	3	$2\ H + 1/2\ O_2 \rightarrow H_2O$	Flue gas
	Sulfur S	0.4	$S + O_2 \rightarrow SO_2$	Flue gas
Contributing to conversion	Oxygen O	15	$2\ O + H \rightarrow H_2O$	Flue gas
	Nitrogen N	0.3	$2\ N \rightarrow N_2$ $N + x\ O \rightarrow NO_x$	Flue gas
	Water H_2O	27	Evaporation	Flue gas
Non-combustibles	Mineral compounds	30	Conversions in the solid, sintering	Ash
Contaminants: halogens	Chlorine Cl	0.75	$Cl + H \rightarrow HCl$	Flue gas
	Fluorine F	0.015	$F + H \rightarrow HF$	Flue gas
Contaminants: heavy metals	Mercury Hg	5×10^{-4}	Evaporation of Hg $Hg + 2\ Cl \rightarrow HgCl_2$	Flue gas, ash
	Cadmium Cd	10×10^{-4}	$Cd + 2\ Cl \rightarrow CdCl_2$	Flue gas, ash
	Lead Pb	0.08	$Pb + 2\ Cl \rightarrow PbCl_2$	Flue gas, ash
	Copper Cu	0.004	$Cu + 2\ Cl \rightarrow CuCl_2$	Flue gas, ash
Organic contaminants	Polychlorinated biphenyls PCB	1×10^{-4}	$PCB + O_2 \rightarrow CO_2$, H_2O, HCl	Flue gas
	Polychlorinated benzenes PCBz	7×10^{-7}	$PCBz + O_2 \rightarrow CO_2$, H_2O, HCl	Flue gas
	Dioxines PCDD Furanes PCDF	35×10^{-7}	PCDD, $PCDF + O_2 \rightarrow CO_2$, H_2O, HCl	Flue gas

chloride evaporates for the most part and passes to the flue gas. The other portion remains in the ash. Organic contaminants are at least completely degraded by oxidation to yield carbon dioxide and water. From the chlorine proportion, gaseous hydrogen chloride (HCl) is generated. A major problem is in catalytic accelerated regeneration of organic contaminants into dioxins and furans from unburnt fragments of organic compounds during flue gas cooling ("de-novo-synthesis").

11.3.3 Thermal Processes Used for Organic Substance Degradation

Thermal processes used for degradation of organic substance may be conceptually distinguished by the amount of reactant, which is either oxygen or air. The amount of air is characterized by the fuel-air ratio being defined as

$$\lambda = \text{amount of air used in process/stoichiometric amount of air}$$

The stoichiometric amount of air exactly contains the amount of oxygen necessary for complete conversion of fuel constituents to the respective oxidation products (see Table 11.3).

In case of addition of excess air, λ is > 1. Thermal processes with $\lambda \geq 1$ are called "incineration" or "combustion". At incineration/combustion, mineral compounds remain as a solid residue called "incineration/combustion ash".

Processes with $\lambda < 1$ are called "gasification". Due to lack of oxygen, complete oxidation is impossible. Products resulting out of the common process conditions are gaseous at ambient temperature and pressure. They may be utilized as a fuel gas or for chemical syntheses ("synthesis gas"). Typical constituents of synthesis gas are carbon monoxide CO, hydrogen H_2, and methane CH_4. Besides, synthesis gases contain the combustion products CO_2 and water. After complete gasification, there are only mineral compounds in the solid residue. A gasification process of technical importance is hard coal gasification used for raw material generation for the petrochemical industry in countries having large availability of hard coal but only little oil reserves, for example, South Africa. For some time, brown coal gasification was used for synthesis gas and energy generation in Germany.

If organic substance is exposed to high temperatures in the absence of air ($\lambda = 0$), there are also degradation reactions by cleavage of chemical bonds. This process is called "pyrolysis". Pyrolysis leads to a completely different product spectrum. There is a solid residue called "pyrolysis coke", mainly consisting of long-chain and cross-linked organic molecules. The hot gas phase comprises a large number of different compounds having a boiling point sufficiently low for evaporation on process conditions. After cooling to ambient conditions, many of these compounds condense, yielding pyrolysis tar.

The most important commercial-scale pyrolysis process is hard coal coking. Pyrolysis coke from hard coal coking is used for iron ore reduction by the blast furnace process. For MSWI in grate firing plants, all the three processes described above are of importance.

11.3.4 Plant Technology

In Fig. 11.9 essential elements of a MSWI plant are sketched in a typical block scheme. These are:

- Waste bunker with charging devices for storage and feeding of waste
- Combustion chamber, where incineration takes place on the grate
- Boiler for flue gas cooling by generation of steam mainly used for power generation by a turbine
- Flue gas cleaning

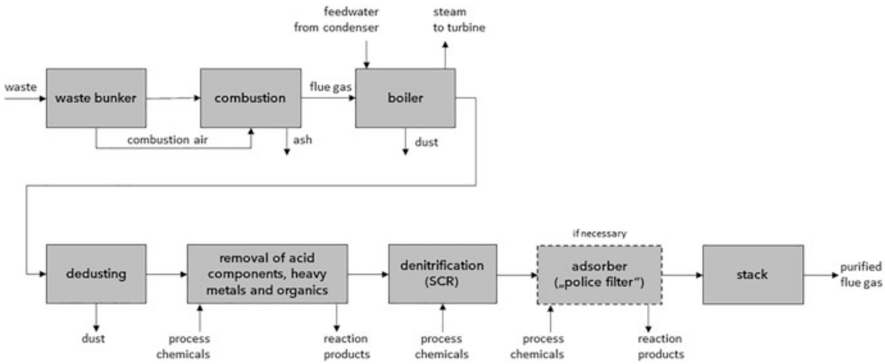


Fig. 11.9 Typical block scheme of a MSWI plant

- Between single plants, large individual differences exist concerning flue gas cleaning. The flue gas cleaning system typically consists of
  - dedusting (fabric filter or electrostatic precipitator),
  - desulfurization (e.g. two-stage washing for removal of HCl, HF, and SO_2),
  - and denitrification (e.g. a fixed bed catalyst reactor for reduction of nitrogen oxides and oxidation of dioxins and furans),
  - together with an adsorption apparatus for post-purification.
- Stack for discharge of filtered flue gas into the atmosphere

The block scheme also illustrates material flows. Waste, combustion air, and process chemicals for flue gas cleaning are inputs to the process. Incineration ash filtered flue gas as well as removed dust and reaction products from flue gas are the outputs from the process.

11.3.5 Waste Bunker

On the one hand, the waste bunker is for storing waste and bridging the periods without waste delivery. Waste supply for about 4–5 days is required for continuous operation. Typically, waste bunkers are about 40–50 m in length, 15–20 m in depth, and 10–20 m in width.

On the other hand, waste is rearranged and mixed in the bunker for homogenisation by means of a crane equipped with a polyp grab. This is necessary to ensure the calorific value to be as uniform as possible.

The feed hopper of the subsequent incineration plant is fed from the waste bunker. Odour emissions from the waste bunker may be avoided by sucking off and feeding bunker air to combustion.

11.3.6 Waste Feeding

In order to avoid uncontrolled input of air, an air-tight waste bed is built in the feed hopper and the subsequent waste chute. Fill level measurements provide continuously information about the fill level of the waste chute. The waste chute is usually water-cooled. A plunger is often used for feeding waste from the lower part of the waste chute onto the firing grate. The mass flow of waste, determining energy input and steam generation power of the boiler, is controlled by the frequency of plunger movement. In order to avoid re-ignition/backfire from the grate into the waste chute, temperature measurements for monitoring and a nitrogen or water based flame extinguishing device are installed in the waste chute.

11.3.7 Combustion Chamber and Firing Grate

Figure 11.10 illustrates the principle of a combustion chamber equipped with a firing grate. The grate consists of bars arranged in rows. The grate has numerous slots for injection of combustion air ("primary air") penetrating the fuel bed from below. With it, primary air is preheated while the grate bars are cooled. This is important in order to limit material corrosion caused by thermal impact.

Charging of primary air takes place via separated, independently controllable zones.

Additional combustion air is added above the grate ("secondary air"). Therefore, combustion takes place in the solid bed on the one hand. On the other hand, hydrocarbons generated in the solid bed evaporate due to high temperatures and burn in the gas phase above the grate. This is explained later in greater detail.

Compared to conventional solid fuels, for example, coal and wood, MSW is problematic with respect to consistence. It is partly felted, partly piled up loosely and is, even after shredding, interspersed with bulky constituents. This leads to an uneven fuel bed on the grate, especially if the waste in the waste bunker has not been mixed sufficiently before. Insufficient mixing increases the risk that there are compacted sections on the grate, which cannot be penetrated by cooling primary air, so they reach high temperatures due to energy transfer from the hot combustion chamber. Besides, in some sections waste is piled up loosely, so it is cooled by large amounts of primary air. In the hot sections, increasing material corrosion appears due to temperature impact, while in the cold zones insufficient burn-out caused by incomplete conversion is observed.

Homogenous incineration requires a continuous rearrangement of the fuel bed by stoking. Stoking is managed by movable grate elements, which do not only transport fuel, but additionally achieve continuous mixing of the solid bed constituents.

Fuel transport on stoking grates is mainly affected by a sloping position of the grate, which is inclined towards the ash output. There are different concepts of stoking:

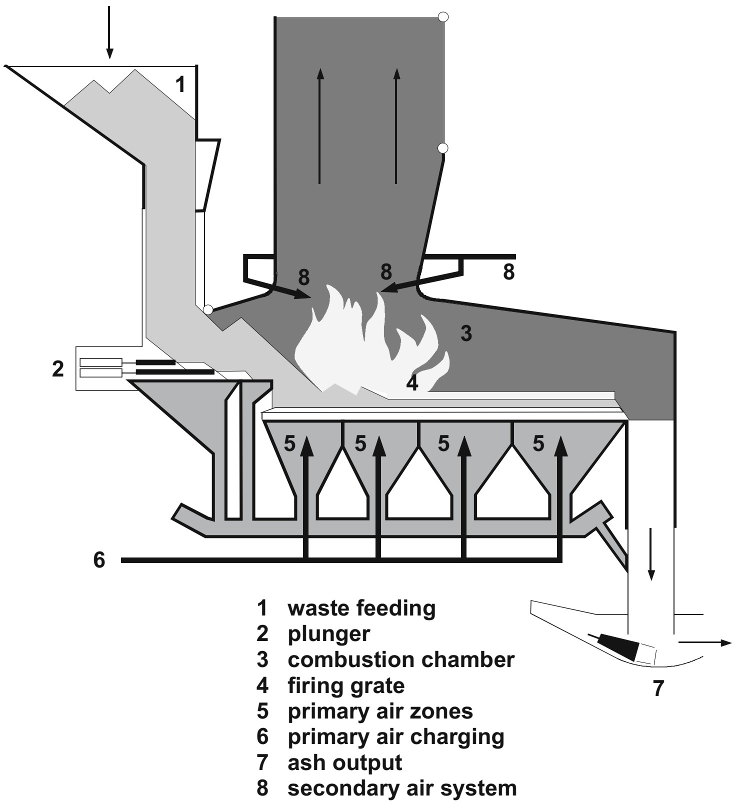


Fig. 11.10 Principle of a firing grate

11.3.7.1 Forward Feed Grate

A forward feed grate consists of grate bars arranged in several overlapping rows being alternately fixed and movable. Figure 11.11 shows a construction example. The recess is for the passage of primary air.

Movable grate bar rows support waste transport by lifting and pushing waste towards the ash output. Stoking takes place to a certain degree by penetrating of the grate bars into the waste bed. It is of disadvantage that on strong stoking waste bed transport is accelerated, so the residence time in the hot reaction zone is shortened, which may lead to incomplete burnout of the solids. Therefore, the grate additionally contains one or two steps where waste falls down being efficiently stoked (Fig. 11.12) without bed transport acceleration.

11.3.7.2 Reciprocating Grate

A reciprocating grate also consists of movable and fixed grate bar rows. The grate is inclined towards the ash output; the lifting movement is directed towards the feeding device. Efficient stoking is reached by continuous pushing of glowing waste

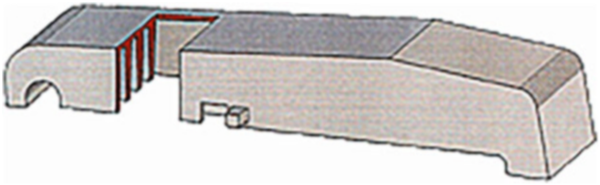


Fig. 11.11 Construction example of a grate bar (Initiative sichere Abfallbehandlung, http://www.isa-vdma.org)

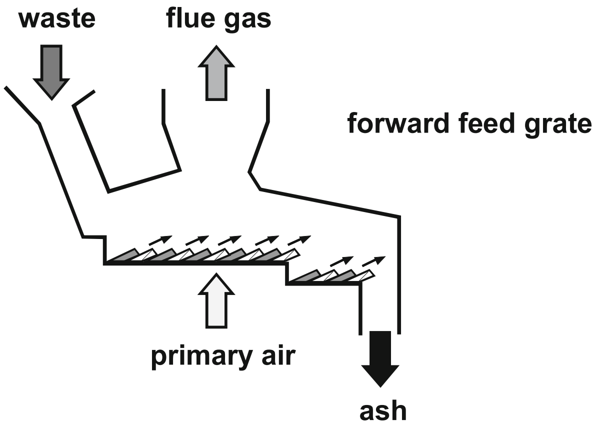


Fig. 11.12 Principle of a forward feed grate

particles towards the top of the grate. Waste transport takes places due to gravitational forces only by rolling over the fixed bed. The backward and rolling movement induce additional mixing of the waste. For this reason, reciprocating grates are steeper than forward feed grates (see Fig. 11.13).

These are the most common system, therefore the third system, the roller grate, is just mentioned.

11.3.8 Sequence of Chemical Reactions During MSWI

Optimum waste burnout requires best conditions for incineration. Those are addressed by the so-called 3t-rule. "3t" stands for time, temperature, turbulence. This means that waste needs sufficiently long residence time and sufficiently high temperature for complete burnout. Furthermore, mixing of the gaseous compounds with oxygen of the combustion air must be provided by high turbulence in the combustion chamber.

Residence time of the solids may be controlled by movement of grate elements and typically amounts to about 1 h. Temperature is up to 800 °C on the grate and up to 1000 °C in the combustion chamber. Turbulence is realized by injection of secondary air, which is mixed with gas to be burnt out as intensively as possible. Particular problem is in the fact that hot gases are difficult to mix due to high

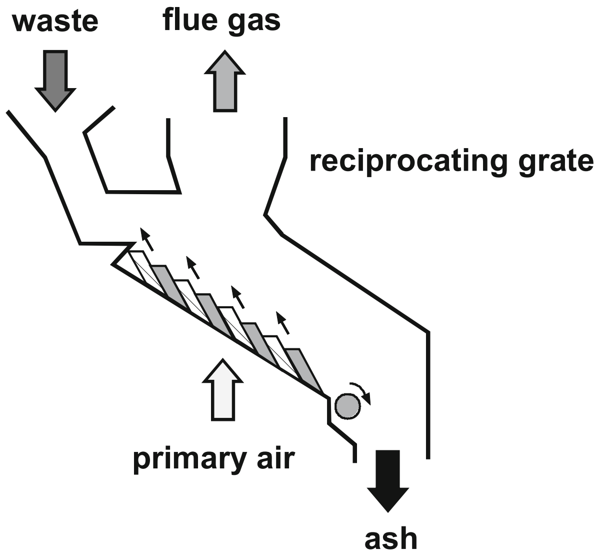


Fig. 11.13 Principle of a reciprocating grate

viscosity because contrary to the viscosity of liquids, the viscosity of gases increases with temperature.

Besides the 3t-rule, other prerequisites must be taken into consideration for optimum incineration. High oxygen concentration must be established in the incineration zone by appropriate excess air. Furthermore, incineration is favoured when the particle size of the solids decreases. For this reason, coal dust combustion is frequently used in power plant technology. Liquids, for example, fuel oil, are also well combustible because they may be finely sprayed. Finally, best combustibility is given for gases.

The better the combustibility of a fuel, the smaller is the air–fuel ratio required for good incineration. Coal dust combustion has an air–fuel ratio of $\lambda = 1.2–1.4$, at oil combustion, λ amounts to about 1.1–1.2. Natural gas combustion operates at nearly stoichiometric air–fuel ratio ($\lambda = 1.0–1.1$). Due to the heterogeneity with regard to particle size and fuel composition, the air–fuel ratio for waste incineration is in the range of $\lambda = 1.6–1.8$.

Since waste is quite problematic for crushing technology because of its composition, shredding is usually not carried out for economic reasons. Only very coarse/bulky material, mainly commercial waste, is coarsely pre-shredded by an additional shredder, which is usually integrated in the waste bunker and then mixed in with the remaining waste. In order to reach good burnout yet, grate firings operate in a two-step combustion process. In the first step, a combustible gas is generated on the grate by thermal degradation of the solid waste. In the second step, this gas is incinerated in the combustion chamber above the grate. The grate with primary air input as first step is used for complete burn-out of the solid phase, the post-combustion chamber with secondary air input as second step is used for complete burn-out of the gas phase.

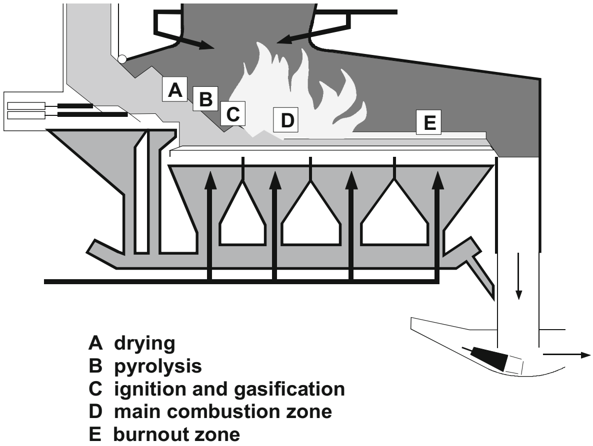


Fig. 11.14 Reaction zones on a firing grate

Figure 11.14 demonstrates the reaction zones where these processes take place. Waste fed onto the grate by the plunger is heated due to energy transfer from the hot combustion chamber. Waste bed temperature does not exceed about 100 °C until waste moisture has evaporated. In this section, primary air is only a transport medium for water vapour (zone A). After water evaporation, the waste bed temperature rises quickly to 300–500 °C. In this temperature range, incineration cannot occur yet. Here pyrolytic degradation takes place without reaction with oxygen of primary air (zone B). Task of primary air is to transport gaseous pyrolysis products into the hot reaction zone above the grate. There they are combusted by homogeneous gas phase reactions supported by secondary air.

Fire ignition takes place when solid waste has reached about 600 °C on the grate. Primary air is not able to combust all molecular fragments released from the solid bed in the ignition zone. Therefore, under-stoichiometric conditions prevail on the grate right after ignition giving rise to waste gasification (zone C). The gasification products, e. g. CO and H_2, must also be combusted by secondary air in the combustion chamber above the grate.

As soon as waste is carbonized in a way that the concentration of gaseous fragments decreases again, oxygen concentration in the waste bed and in the gas phase directly above is hyper-stoichiometric. In this zone (zone D), incineration takes place and a fire may be observed on the grate.

At the end of the grate, fire dies down leaving the solids in an embers bed where direct incineration takes place by heterogeneous gas-solid reactions. This zone is called “burnout zone” (zone E).

Drying and pyrolysis are endothermic, i.e. energy-consuming, reactions. Necessary uptake of energy is possible by heat transfer from the hot combustion chamber and from the rear grate sections, where exothermic, i.e. energy-generating, processes of gasification and combustion take place.

11.3.9 Variations of Combustion Chamber Design

Combustion chamber design depends on the characteristics of the fuel to be expected. It may be differentiated between counter-current, co-current, and middle flow combustion chambers (see Fig. 11.15).

At counter-current flow combustion, the entry into the flue gas channel is located above the front part of the grate. The waste bed and the hot flue gas move in counter-current flow because gasification and incineration of the waste bed take place further towards the back of the grate. An advantage of counter-current operation is in the possibility of fast heating and efficient drying of waste by hot gases at the front of the grate. Therefore, counter-current flow combustion is used for moist waste or waste of particular low calorific value relying on ignition support from hot gases.

At this variation, the pyrolysis zone and possibly parts of the gasification zone are located directly below the entry into the flue gas channel. For this reason, there is a danger that a portion of the reaction products (e. g. carbon monoxide) draws off into the flue gas channel without being combusted by contact with hot, oxygen-rich gases directly above the solid bed. In this case, combustion must take place in the free space of the combustion chamber, hence remaining frequently incomplete.

At co-current flow combustion, the access to the flue gas channel is above the back end of the grate. Consequently, hot reaction gases and the solid fuel bed pass the combustion chamber in the same direction. Energy transfer between reaction gases and upper zones of the solid bed, supporting ignition, is missing. So, this kind of operation is only appropriate for well ignitable waste of high calorific value. The advantage over counter-current flow is in the fact that gasification and pyrolysis products are forced to pass the hot zone right above the grate where they may be burnt out to a great extent already.

Middle flow operation is a compromise between the two extremes.

MSW to be expected today has a slightly higher calorific value than it had one or two decades ago. Thus, modern MSWI plants normally use co-current or middle flow operation.

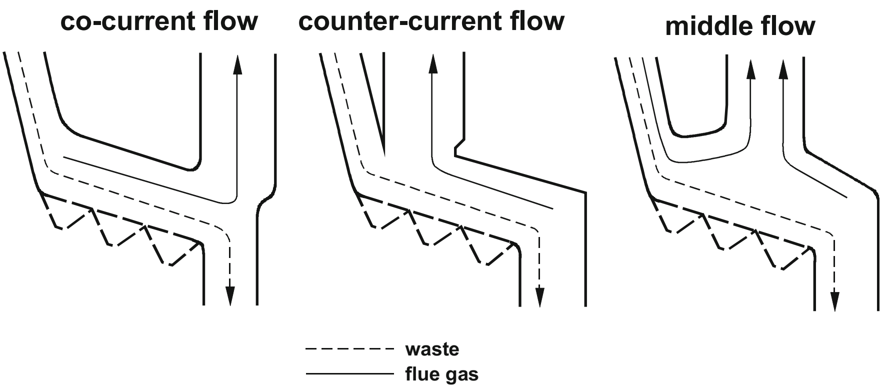


Fig. 11.15 Variations of combustion chamber design

11.3.10 Overall Plant Design

During planning of a MSWI plant, central points are the average amount of waste to be combusted per day and the resulting capacity the plant must be designed for. In that respect, adjustment of the waste mass flow to the flue gas cooling and energy recovery by the boiler is of major importance.

Figure 11.16 shows a diagram for the operational range of MSWI. Thermal output (on the *y*-axis) is plotted against waste mass flow (on the *x*-axis). For constant calorific values, there is a linear correlation between the two quantities. Plotting this correlation for different calorific values H_u yields a group of straight lines. The quantity of a "lower calorific value H_u" employed here stands for the energy released on incineration assuming water to be present in the vapour-state.

Within the group of straight lines, the operational range of a MSWI plant and its technical limits may be recognized as a grey field in Fig. 11.16. The limiting lines are explained in the following:

11.3.10.1 Line 1

Line 1 marks maximum waste mass flow, which is the basic quantity for transport system design. If waste exceeds maximum flow, transport of waste on the grate and removal of ash would no longer be possible. Furthermore, the residence time of the solid would be too short to ensure sufficient burnout because of the high throughput.

11.3.10.2 Line 2

Line 2 designates minimum waste mass flow amounting about 40% of maximum throughput. On falling below minimum flow, feeding of waste by the plunger is

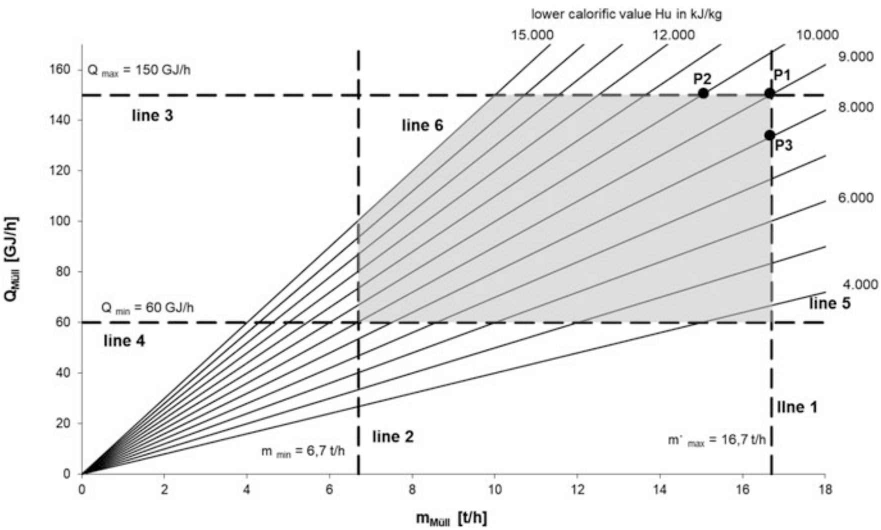


Fig. 11.16 Operational range diagram of MSWI

getting unsteadily. The waste bed becomes thin and uneven, so the resistance for primary air flow is irregular. This leads to cold and hot regions on the grate resulting in bad burnout and increased material corrosion, as already addressed in Sect. 5.3.

11.3.10.3 Line 3

Line 3 is the upper limit of energy input given by the capacity of the boiler. In many cases, boiler dimensions are chosen in a way that line 3 meets the intersection of the line of maximum waste mass flow (line 1) and the straight line characterizing the waste calorific value to be expected (here 9000 kJ/kg). This point may be called "point of optimum operation" (P1).

11.3.10.4 Line 4

Line 4 stands for the corresponding limit in the region of low energy input. If energy input is too low, the amount of steam produced by the boiler is below the operation limit of the turbine. Boiler operation is also endangered, because natural circulation of water and steam, which is the operational basis of most waste incineration boilers, breaks down.

Finally, a reduction of the flue gas volume flow may be observed with decreasing energy input. This brings about reduced flue gas velocity leading to increasing dust precipitation in the flue gas channel.

11.3.10.5 Line 5

Line 5 characterizes minimum calorific value of waste. Waste of still lower calorific value is no longer combustible without support of additional, high-grade fuel.

11.3.10.6 Line 6

Line 6 determines maximum calorific value. Exceeding line 6 causes local ash softening and exorbitant temperatures in the solid bed. Soft ash partially flows into the air slots of the grate, solidifies after cooling, and blocks the air channels. Exorbitant solid bed temperatures involve the risk of increased grate material corrosion due to thermal stress.

Contrary to power plant incineration, changing calorific values of fuel must be considered for MSWI. In case of an increase of the calorific value, the point of optimum operation shifts on line 3 to the left in the direction of lower throughput (P2), with the result of decreasing revenues because waste incineration is paid by weight of combusted waste or a special feed-in tariff for the produced electricity.

For this reason, the boiler is most times dimensioned slightly larger, so the energy output at the operational point is somewhat lower than maximum energy output (P3). In this case, increase of the calorific value of waste may be compensated to a certain degree without reduction of waste mass flow.

11.3.11 Flue Gas Cleaning

The flue gas cleaning of a WtE plant is individually designed based on the waste composition, its pollutants, and the legal requirements in the project country. For compliance with emission limits conceptually different measures may be used:

1. *Prevention of pollutant formation*
   (a) limitation of pollutant input, e.g. heavy metals, nitrogen, or halogens (if possible),
   (b) reduction of particle deposition in the boiler and prevention of long residence times in a temperature range between 250 and 400 °C (rapid cooling of flue gas reduces formation of dioxins and furans (de novo-synthesis)),
   (c) reduction of the so-called fuel-NO_x (see Chap. 4) by generation of a reaction zone with oxygen deficiency.
2. *Thermal destruction*
   (a) conditions for an optimal burn-out guarantee complete combustion of carbon monoxide (CO) and organic pollutants (e.g. polyaromatic hydrocarbons, polychlorinated biphenyls (PCB), polychlorinated dibenzodioxins and -furans from the input).
   Points 1 and 2 are called primary measures, being integrated in the incineration process. For controlling carbon monoxide emissions, only primary measures are available.
3. *Chemical conversion*
   (a) feeding of oxidating agents (e.g. H_2O_2 for PCDD/F-destruction),
   (b) catalytic reactions (e.g. NOx-reduction).
4. *Physical separation*
   (a) filtration, e.g. for particle separation (dedusting),
   (b) absorption in washing liquid,
   (c) adsorption on solid adsorbent.
5. *Physical separation with chemical reaction*
   (a) scrubbing with alkaline agents,
   (b) scrubbing with precipitating and coagulating agents.
6. *Tertiary measures ("police filter")*
   (a) subsequent, non-selective separation of several pollutants for compensation of emission peaks, and in case of failure of secondary cleaning devices.

   Points 3–5 are called "secondary measures". Point 6 is a "tertiary measure", being subsequent to incineration. Secondary and tertiary measures of flue gas treatment in waste incinerators are subject of this paper.

Primary measures are discussed in the papers dealing with municipal and hazardous waste incineration.

A typical flue gas cleaning system is divided into four parts (denitrification, dedusting, desulfurization/reduction of halogen components, and tertiary measures). The specific technologies chosen for flue gas cleaning are mainly related to the legal provisions (flue gas emission limit values) of the respective country.

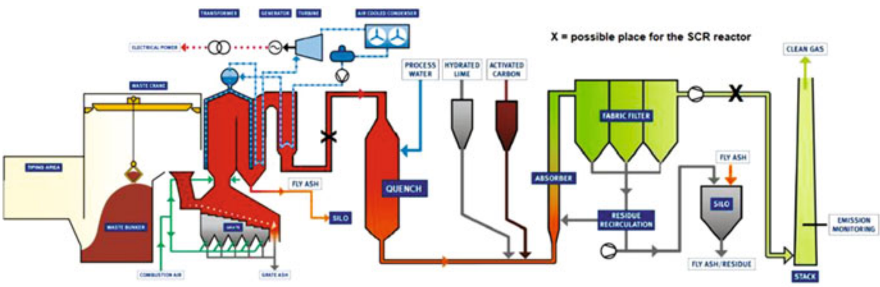


Fig. 11.17 Typical flow diagram for waste to energy plants (Energetic flow diagram of a thermal municipal waste treatment, Müllheizkraftwerk GML)

The state of art plant configuration of waste incineration plants is shown in Fig. 11.17.

11.3.11.1 Denitrification

Nitrogen oxides (NO_x, above all NO and NO_2) are generated in waste incineration from the nitrogen content of fuel (the so-called fuel-NO_x), as well as by oxidation of nitrogen molecules as the main part of combustion air at high temperatures (the so-called thermal NO_x).

Removal of nitrogen oxides is possible by selective noncatalytic reduction (SNCR) and by selective catalytic reduction (SCR), respectively. In each case, ammonia is injected into the flue gas stream, reducing nitrogen oxides to yield water and nitrogen. At common process conditions (see below), all compounds are gaseous.

$$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$$

$$2\ NO_2 + 4\ NH_3 + O_2 \rightarrow 3\ N_2 + 6\ H_2O$$

$$6\ NO + 4\ NH_3 \rightarrow 5\ N_2 + 12\ H_2O$$

$$6\ NO_2 + 8\ NH_3 \rightarrow 7\ N_2 + 12\ H_2O$$

For SNCR, high temperatures (850–900 °C) and a large excess of ammonia are necessary. Storage of ammonia requires appropriate devices equipped with expensive security technique. Therefore less harmful substances, like urea or ammonia water are commonly used. The chemical reactions are comparable.

In most cases, SCR is operated at temperatures of 250–350 °C. Applied catalysts (see Fig. 11.18) are, for example, honeycomb catalysts made of ceramic, being doped with tungsten trioxide and vanadium pentaoxide, respectively.

Degrees of conversion depend on the size of the catalyst reactor and on the ratio of NH_3 and NO_x. Space velocity ("s. v."; denoting, how many times per hour catalyst volume is filled with fresh flue gas) is a reciprocal measure of reactor size. In larger reactors (having lower space velocities) and for larger amounts of ammonia, higher

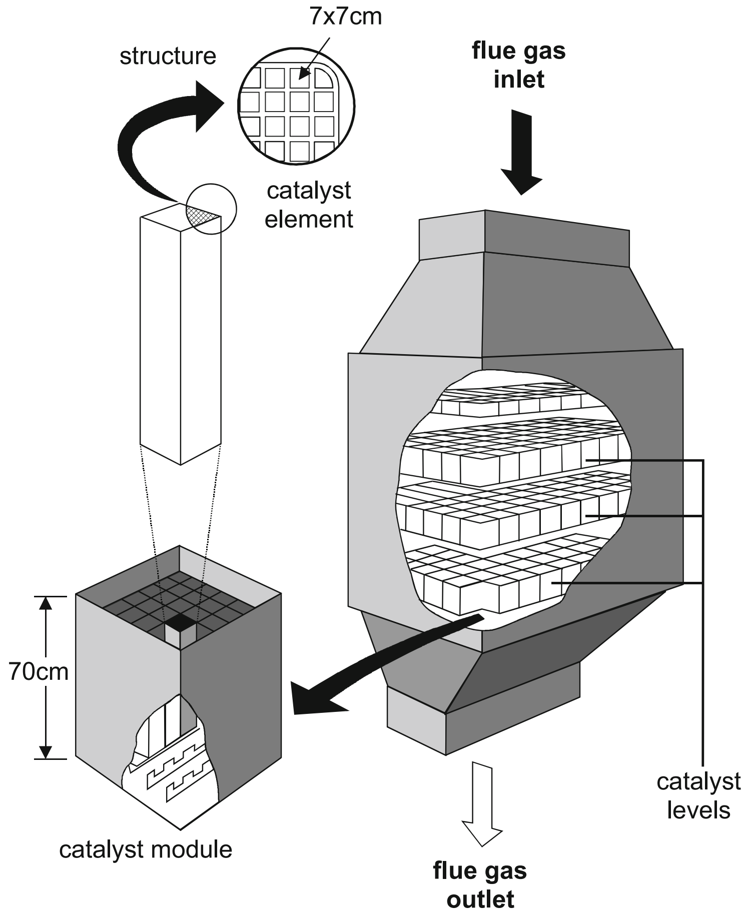


Fig. 11.18 Catalyst design

degrees of conversion are reached. At this point, economic optimisation (investment costs vs. operating material costs) is required. If ammonia excess is too high, emission limit values of NH_3 may be exceeded due to unused NH_3 slip.

SCR may be installed in the "high dust" region before flue gas cleaning. Then, heating of flue gas is not necessary. Conversely, serviceable life is shorter because of the dust loading.

In case of installation in the "low dust" region after dedusting and scrubbing, flue gases must be re-heated before SCR may work. After scrubbing, flue gas has a temperature of approximately 70 °C. Heating to 270 °C takes place in a recuperative heat exchanger, operating in counter-current, by processed flue gases coming from the catalyst reactor. Temperature change within the heat exchanger is portrayed at the bottom left of Fig. 11.13. The ratio $\Delta Q/Q_{tot}$ runs from 0 to 1, representing the proportion of exchanged heat at some point of the apparatus compared to total exchanged heat.

In order to make continuous heat exchange possible, a continuous temperature difference of the flue gas streams in counter-current must be maintained. Thus, flue gas is heated after leaving the heat exchanger from 270 °C to 300 °C by a gas burner or a steam heat exchanger or a recuperator, establishing a temperature difference of 30 K to heat a cold flue gas, which is leaving the counter-current apparatus with 270 °C (e.g. low temperature catalyst) or lower.

After heating, injection of a NH_3–H_2O mixture takes place, and then flue gas passes the catalyst reactor. After removal of nitrogen oxides, flue gas enters the heat exchanger to be cooled from 300 to 100 °C.

The choice for a SNCR (selective noncatalytic reduction) or a SCR is depending on the nitrogen-oxide content of the flue gas (denitrification) and the emission limit to be reached.

11.3.11.2 Dedusting and Desulfurization

Main components of dust are Si, Al, Fe, und Ca, creating a mineral matrix. Minor components are especially heavy metal chlorides, sulfates, and oxides. During cooling of flue gas, toxic organic and inorganic substances can condense on dust particles if the residence time is sufficient, so dust must be considered as hazardous waste in this case. This danger can be significantly reduced with short residence times. In waste incineration plants, particles are mainly precipitated by electrostatic precipitators, wet-electrostatic precipitators, and fabric filters (“textile filters”). Cyclones are rarely used.

Dust is primarily contained in the fly ash coming from the steam generator and byproducts coming from the upstream arranged stages of the flue gas cleaning plant. In this configuration the fabric filter is utilized in a form of bag filters. The flue gas enters from the outside to the inside through the fabric of the bag filters. Separated dust forms gradually an increasing filter cake as the flue gases through the fabric. Moreover, the remaining dust still has a reactive sorbent cleaning effect. The bag filters are periodically cleaned by means of compressed air pulse. Separated dust is collected in an extraction hopper of the bag filters, transferred and stored in a silo until pick up by a silo truck.

Before entering a fabric filter the flue gas needs to be cooled down by a quench by injecting water. The temperature is cooled down from about 200–230 °C (after the economizer) to about 140 °C to increase the reactivity of the flue gas with the injected additives. In case of a very efficient boiler with low exit temperature a cooling or quench is expendable. Between the quench and the fabric filter, there is a reaction section, in which hydrated lime and activated carbon are injected for flue gas desulfurization and reduction of halogenated compounds of the flue gas. Separation of solid matters proceeds in the fabric filter, e.g. dust from the flue gas.

In fabric filters, filter bags made of PTFE are used, being very resistant against chemical substances. In order to avoid caking, filter fibres have a smooth surface. The distance between two fibres in the filter amounts to 50–150 μm, so these fibres alone have only a weak sieving effect. In real process, a porous layer of filter cake is quickly generated, which acts as a filter in its turn. Because of that, a fabric filter reaches degrees of separation of more than 99.8 wt.%. In the dedusted flue gas, only fine particles of 0.05–5 μm in diameter remain. Within the filter housing, bags are arranged to groups, which may be separated from each other. Thus, during cleaning or maintenance of one filter group, the other groups may stay in operation. If pressure loss is too high, the filter must be cleaned. For that purpose, filter bags are blown from inside by compressed air, exfoliating the filter cake. A residual load remains in the depth of the filter fibre.

$$1/2\ O_2\ (g) \rightarrow CaSO_4\ (s) + H_2O\ (g)$$

$$SO_3\ (g) + Ca(OH)_2\ (s) \rightarrow CaSO_4\ (s) + H_2O\ (g)$$

$$2\ HCl\ (g) + Ca(OH)_2\ (s) \rightarrow CaCl_2\ (g) + H_2O\ (g)$$

$$2\ HF\ (g) + Ca(OH)_2\ (s) \rightarrow CaF_2\ (g) + H_2O\ (g)$$

In case of dry flue gas cleaning, the degree of separation strongly depends on the stoichiometric factor, being equivalent to the ratio of added and stoichiometric amount (this means minimum amount corresponding to the chemical reaction equation) of reagent.

In order to abstain from tertiary measure activated carbon or coke or similar reagents like zeolites are injected upfront of the fabric filter as well. The chemical reactions are as described below.

11.3.11.3 Tertiary Measures

In activated coal/coke adsorbers, flue gas passes one or several layers of activated coke or activated carbon, respectively. Possible flow designs are “cross-flow”, “counter-current flow” as well as “recycled cross-flow”. In waste incineration plants, mainly cross-flow technique is used. Solid bed layers act as a particle filter for dust and as an adsorbent for gaseous compounds. For that reason, heavy metal compounds, HCl, SO_2, and organic compounds (PCDD/F, PAK, etc.) may be removed simultaneously in one apparatus.

As an example, removal of mercury is illustrated. Prerequisite is an adsorption and subsequent reaction of sulfur oxides and water, yielding sulfuric acid on the carbon surface. The latter reacts with elemental mercury to generate mercury sulfate, which may be removed together with loaded adsorbent.

$$SO_2\ (g) \rightarrow SO_2\ (\text{adsorbed})$$

$$SO_2(\text{adsorbed}) + O_2\ (g) + 2\ H_2O\ (g) \rightarrow 2\ H_2SO_4\ (\text{adsorbed})\ (\text{in water film})$$

$$2\ Hg^0 + 4\ H_2SO_4(\text{adsorbed}) \rightarrow 2\ HgSO_4(\text{adsorbed}) + 2\ SO_2\ (g)$$

In order to support adsorption, operating temperature should be as low as possible. Conversely, condensation of water in the pores of the adsorbent must be prevented. Optimum temperature in practice is about 120 °C.

Occurrence of local superheating must be prevented by respective safety measures. Within the solid bed, generation of such "hot spots", where cold oxidation (CO-generation at low temperatures) takes place, is possible because of uneven flue gas flow, leading locally to insufficient heat loss. For monitoring purposes, CO-concentration difference of incoming and outgoing flue gas is measured. In case of exceeding a significant threshold, the reactor is taken out of the hot flue gas flow and cooled by circulating cold gas in the apparatus. Additionally, inert nitrogen may be used to stop oxidation reactions.

Activated coal/coke adsorbers are required to compensate concentration peaks occurring even in case of normal operation, as well as to limit emissions in case of a breakdown of upstream cleaning stages. For that reason, these devices are also called "police filter".

11.4 Design references and project development

The capacity of 225,000 t/year of the Iqony WtE Plant "T.A. Lauta" is a typical capacity of incineration plants generating around 20 MW of electricity (see Picture 11.3). In general, heat or chill can be produced in co-generation. The waste is turned into slag, ashes, and residues in a much reduced amount and volume compared with the original characteristics of the waste by approximately 50%,[3] which can be mostly recycled as scrap metal and building material. For example, slag can be used as recyclable material for additional benefit. From a perspective of an engineer, owner, and operator of WtE plants, a lot of interesting visions of WtE plants need to be brought back to earth of facts and figures. The key drivers are the treatment and reduction of waste and the production of electricity, i.e. a WtE plant cannot compete with the technology on the electricity market alone.

Based on an incineration capacity of 150,000 t/year, the German development agency GIZ determined following costs for a WtE plant:

Considering economy of scale the investment and operation cost can be significantly optimized. But a large incineration site will most probably require advanced technology in Indian countries also due to their environmental impact and public acceptance.

Figure 11.19 shows an example of an advanced plant concept with a high sophisticated flue gas treatment.

The WtE plant T.A. Lauta complies with very stringent emissions limits, which are below the thresholds of the respective German directives (17.BImSchV). Due to the design and operational standard the measured emissions are far below these limits as shown in Fig. 11.20:

[3] Waste to Energy – key element for sustainable waste management; Brunner, Rechenberger, 2015.

Picture 11.3 Iqony WtE Plant "T.A. Lauta" in Saxony, Germany

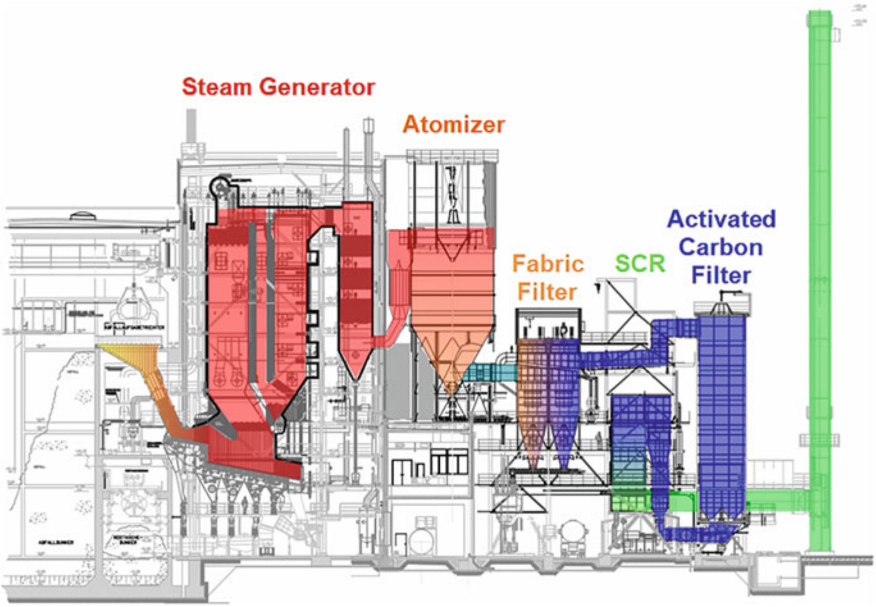


Fig. 11.19 Cross-section of "T.A. Lauta" in Saxonia, Germany

The WtE plant T.A. Lauta has two combustion lines and a capacity of 225,000 tons domestic waste per year and was engineered and developed by Iqony Solutions GmbH. At least the flue gas treatment is adapted, respectively, "simplified" in

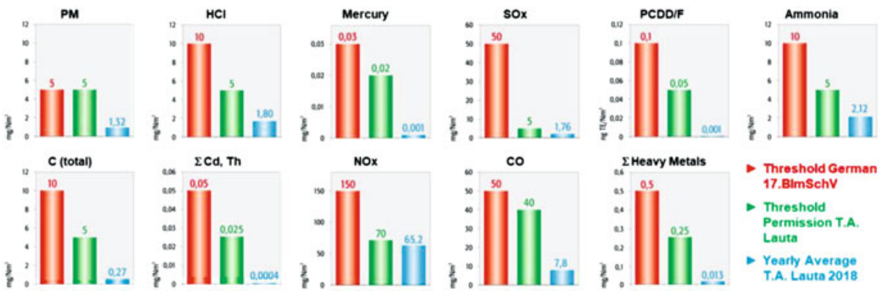


Fig. 11.20 T.A. Lauta—emission limits and actuals

Table 11.4 Cost estimate for WtE plant (benefits and challenges of waste-to-energy power plants in Africa, Dr. Jens Reich, 2018)

	Investment (Mio. EUR)	Total cost per ton (EUR/t)	Revenue from energy sale per ton (EUR/t)	Cost to be covered by waste per ton (EUR/t)
Cost basis EU advanced, 2 lines	135–185	260–295	27	200–235
Emerging country basic, 1 line	30–75	42–90	2–10	40–80

emerging countries complying with international standards to downgrade the technology to a base case.

The overview in Table 11.4 clearly shows that a WtE plant requires revenues of at least 40 Euro per ton coming along with the waste as gate fee, or similar. In general people are willing to pay 0.2– 0.4% of the GDP for waste management, i.e. a GDP per capita of 250–2500 Euro per capita is essential for a waste incineration project (benefits and challenges of waste-to-energy power plants in Africa, Dr. Jens Reich, 2018). Revenues from the energy sales cannot grant the economic feasibility of a WtE plant. There are several good reasons for waste incineration as mentioned before and it is a task of the government or the sovereign to support this development, if the economic hurdle is too high for private initiative, by subsidies, sponsored gate fees, special feed-in tariffs for electricity, etc.

After this fundamental precondition, the WtE capacity and the local environment, e.g. permission requirements, legal structure, necessary infrastructure strongly influences the

- investment and development costs,
- project schedule, which may be up to five and more years,
- long-term, bankable proof of the supply chain on quantity and price.

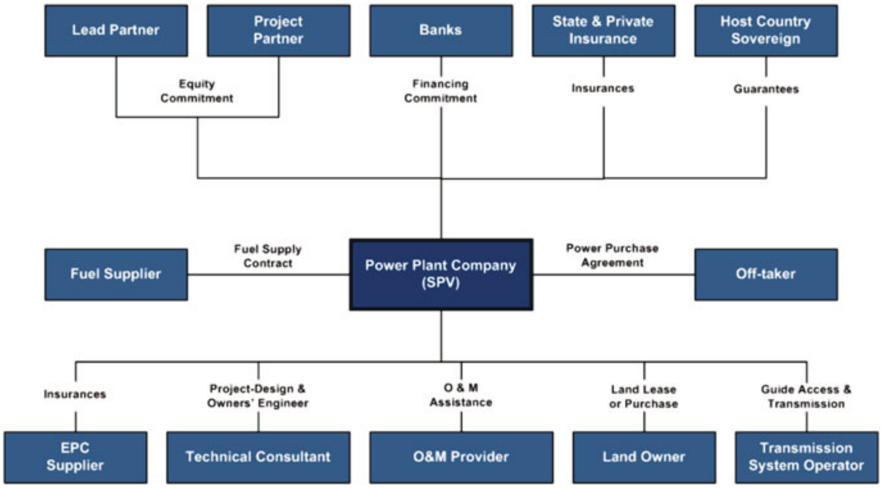


Fig. 11.21 "Project Spider" (decision tree of capacity building for power generation, Reich, PowerGen Africa 2015)

The general statements like "there is a lot of waste" must be confirmed by reliable and testable fact and figures. Last but not least, the generated electricity and, if possible, heat or chill need off-takers. From a view of a project developer and financing institutes both fuel-supplier and off-taker(s) should fulfil certain requirements like general commitment to deliver waste/take off power, financial capability, and credit-status.

The lower end starts at several hundred thousand Euros for small units neglecting non-industrial size solutions. Very large power plant projects in the GW range require billions of Euros in investment. Typically, the development cost can be derived from the investment cost. In the project start-up and feasibility phase, 2–5% and in the mature development phase 10–20% of the investment cost is necessary as risk capital. The actual amount depends on factors like time schedule, partners, own capabilities, etc. Fundraising is quite challenging, especially for entrepreneurs and new companies in the business. The challenge is to get a clear picture and answers about the entire project structure as shown in Fig. 11.21. On the one hand, all boxes should be filled with details such as approach, partners, contracts, etc. On the other hand, this so-called project spider is a lead to a successful project development approach and an illustration of the complexity of this.

11.5 Case Studies

Iqony Solutions GmbH has prepared numerous studies for waste-to-energy power plants. The topics range from general, available framework to the implementation of novel technologies such as storage technologies (e.g. atmospheric hot water tank). Some relevant studies will be described in the following chapters. In general, the concept of a WtE plant with regard to technology, pre-treatment etc. needs to be individually designed on the local conditions and waste composition.

11.5.1 Indonesia

Iqony Solutions GmbH prepared a study for a general framework of waste-to-energy power plants in Indonesia in 2018. The focus of this study was on the plant technology for a waste incineration plant. Iqony Solutions GmbH decided to choose a robust and durable state of art plant configuration (see Picture 11.4). Treatment of municipal solid waste, in particular in large cities and densely populated regions with rapidly increasing living standards, as it is currently the case in Indonesia, repeatedly creates immense problems. Due to the lifestyle of the Indonesian population, which was strongly rural until a few years ago, landfill capacities for waste disposal were largely sufficient for the accumulated waste quantities. By cause of the rapidly increasing living standards, the waste quantities exceed the landfilling capacities.

Independently of landfilling of municipal solid waste this kind of waste treatment requires large-scale land and the longer unpredictable duration for adverse impacts on the environment. Landfill areas are subject to uncontrolled adverse impacts on biological, chemical, and physical processes. Due to undetermined quantity of various organic and inorganic substances and their reactions, negative environmental reactions occur in the landfill areas, which are unpredictable on long-term basis. By burning the waste, on the one hand, the volume is reduced by a factor of about 10 and on the other hand, electricity and heat or steam can still be obtained from the heat produced during combustion. Furthermore, residues of the remaining substances (e.g. grate slag or ashes) are mostly useable (e.g. for road construction). Furthermore, all pollutant components are separated in sufficient quantity in the flue gas cleaning system so that environmental impacts are greatly reduced.

The fuel composition of the Indonesian waste is different to the European waste composition. Especially the organic fraction is dominating the fuel composition (see Table 11.5). So the net calorific value is lower and the water content higher in comparison to the “German” waste composition.

Picture 11.4 Example of a landfill site in Indonesia (own pictures, taken by SES in Indonesia)

Table 11.5 Fuel composition of Indonesian municipal solid waste (waste consumption in Indonesia, PT Mustika Limbah Multiguna)

Type/day	% MSW composition (%)	MSW (metric ton)	Moisture content (%)	Dry MSW (kg)	Heat value (Btu)	Btu content (KJ/T)	Specific energy content (Btu/T)
Glass	0.004	0.08	0.03	0	60	5	60
Rubber	0.442	9.11	–	9	10,000	91,052	10,000
Wood	3.852	79.35	0.60	32	8000	634,810	8000
Paper	10.953	225.63	0.06	212	7200	1,624,549	7200
Metal	0.405	8.34	0.02	8	300	2503	300
Organic	57.211	1178.55	0.70	354	2000	2,357,093	2000
Plastic	12.746	262.57	0.04	251	14,000	3,675,946	14,000
Sharps	0.311	6.41	0.01	6	7000	44,846	7000
Textile	7.157	147.43	0.10	133	7500	1,105,757	7500
Garden	6.910	142.35	0.17	119	5660	805,621	5660
Ceramics	0.009	0.19	0.17	0	6172	1144	6172
Total	100.000	2060		1124		10,343,326	67,892

The fuel used is the deciding factor for selecting the technology and the subsequent calculations for the energy and mass balances. The most important criteria is the lower calorific value, from which the possibility of the self-contained combustion of the fuel can be derived, without having to add another, higher calorific fuel. Because at a specific net calorific value (approx. 4.5 or 5 MJ/kg), the fuel does not provide enough thermal energy. This calorific value results from the proportion of each single fraction of the waste.

The Indonesian waste is dominated by the organic fraction. Out of this, the net calorific value is around 3.5 MJ/kg (in Germany mostly like 7–15 MJ/kg). So the waste has to be pretreated. Either the organic fraction will be separated or the waste has to be dried (reduction of the water content). By separating the organic fraction it would be possible to use this fraction in a biogas plant for power generation or to feed the biogas into the local gas network. Figure 11.22 shows a process scheme of a biogas plant.

This biogas plant would be a topping of the plant configuration even it is possible to separate the organic fraction of the delivered waste, which should not highly differ in composition. This does not necessarily represent the standard of a waste incineration plant. This option was taken into account at the request of the Indonesian government to give the project a green touch.

11.5.2 India

11.5.2.1 Introduction

Kochi is a fast developing metropolis located in South Western state of Kerala in India. Kochi has a population of 602,046 as per 2011 census and area of 107.13 km^2. It is one of the most densely populated cities in India (about 5620 persons/km^2) with Rs. 63,599 per capita income (at 2004–2005 constant price) and is also among the highest per capita income cities in the country. Kochi is also one of the selected smart cities and attracting IT industry. Kochi therefore, apart from Swachh Bharat Mission Stipulations, has high concern for its efficient waste management. Kochi Municipal Corporation (KMC) estimates 420 t of solid waste/day. There is paucity of sanitary landfill areas.

11.5.2.2 Project Conception

In the year 2000, the Indian government notified the "Municipal Solid Waste (Management and Handling) Rules 2000", which makes it compulsory for each municipality to introduce a scientific solid waste management system. KMC had been processing Municipal Solid Waste (MSW) at an existing treatment plant which had become inadequate and was no longer functioning properly.

Considering the above as also rapid future growth, limitation of sanitary landfill places and environmental pollution considerations, KMC decided to develop "MSW to energy plant (WtE)" and entered into an agreement with G.J. Eco Power Pvt. Ltd. (G.J.E.P) to set up a plant on BOT (Build, Operate, Transfer) basis, based on:

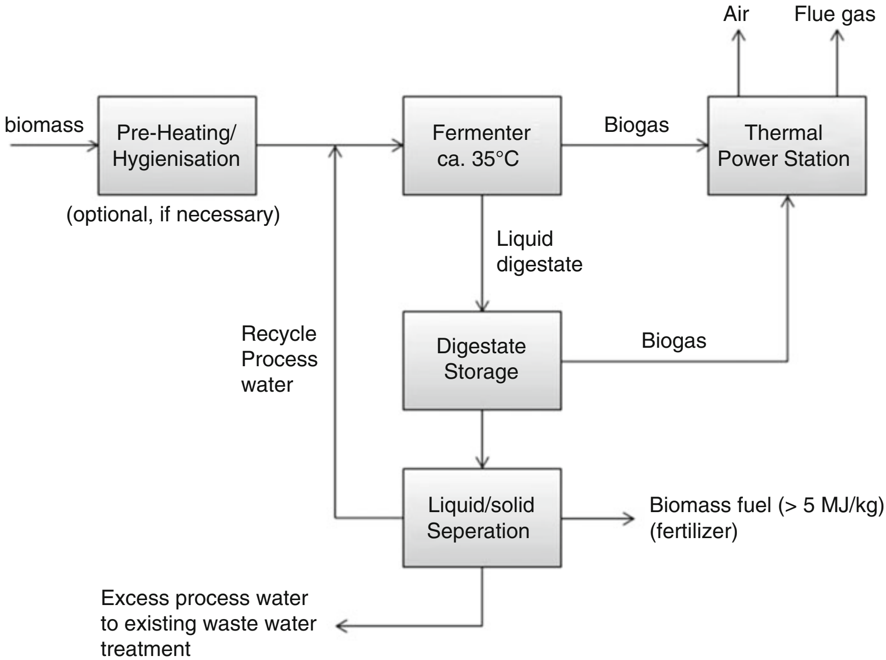


Fig. 11.22 Simplified process scheme for a biogas plant

1. Thermal technologies—gasification or pyrolysis considering environmental quality as prime requirement of state of Kerala
2. Solid waste disposal, to the extent feasible by recycling/recovery of reusable items and manufacturing of value added products
3. Minimum residual for landfill
4. Leachate management
5. Air quality control

KMC committed a MSW supply of 300 t/day (min.) to the project. The site for the project was allocated by KMC in vicinity to an existing MSW dump where about 1.2 million tons of waste has piled up. Part of the water requirement of the project will be met by freshwater intake from Kadambrayar river/borewells and rest to be treated/recovered wastewater generated by plant. It is required to be a zero water effluent plant. Power generated is to be evacuated through a 33-kV line up to nearest 220-kV Brahmapuram grid substation (about 150 m distance). The Kerala State Electricity Board (KSEB) has entered into a Power Purchase Agreement (PPA) with 20 years term (Co-terminus with B.O.T. concession Agreement) to purchase all power generated at the plant at Rs. 6.67/KWh + taxes—firm for full term. The plant is not to be subject to dispatch and full power generated has to be taken off by KSEB.

11.5.2.3 Waste Composition

As per the basic plant requirements (concession agreement with KMC), the WtE plant is to use gasification and syngas as fuel. For sizing of plant and equipment, it is crucial to understand the MSW—its availability—quantity and mechanism/equipment required to convert it to fuel (RDF). The RDF for gasification to meet:

- Moisture content—low
- Calorific value at least 12 MJ/kg
- Free of toxic substances
- Must be of right density

As a first step, towards the above process, the populace/urban areas, that would feed the plant, were identified. The KMC is the core area of Kochi. Kochi Metropolitan area includes, besides KMC, two municipalities and many panchayats. The population projections of Kochi Metropolitan area, forming hinterland for the WtE project are about 2.1 million (2011 actual) to about 3.5 million in 2031.

The Kochi Metropolitan area is generating about 1000 t/day of municipal solid waste, averaging about 400 gm/capita/day which is consistent with studies carried out by National Environmental Engineering Research Institute (NEERI).

A study for characterization of MSW was carried out for planning collection, transport, recycling, evaluation of RDF produced, treatment systems, etc. Samples for this study were collected based on Landesumweltamt Brandenburg 1998, Zwiesele 2005, Bulletal 2005 recommendations from the "Solid Waste Analysis Tool" prepared by the European Commission 2004 (EC SWA tool). This methodology ensures a statistically correct sampling of the waste.

Samples were collected from trucks, which had directly collected waste from source. Samples were collected from different areas/different days of the week/ different economic strata/different consumer profile.

Number of leachate samples was also collected. The preparation of samples and chemical analysis were according to LAGA PN98 guidelines (2004) and the DIN 19698 (2014), respectively.

Analysis Summary

The data were collected over a period of 6 years from 2013 to 2018 and the summary of the characteristics was noted as indicated below (see Fig. 11.23 and Tables 11.6 and 11.7):

The lower calorific values of the constituents are:

The Moisture Content

It is noted that it varies between 40 and 75%, especially during the different seasons. After analysis, it is planned to design the plant considering:

1. Moisture to be reduced from about 65% to 25%.
2. Inert metals to be segregated.
3. Reusable like metal, debris, paper, and paper board to be recycled.

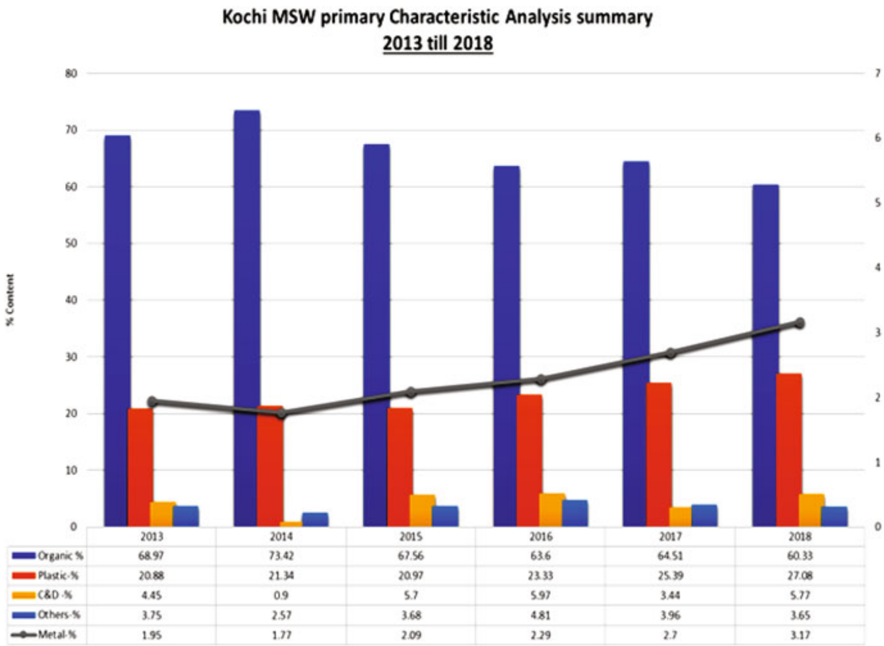


Fig. 11.23 Kochi design waste composition (D 2.2 Waste Profiling, Prepared by FhG-IBP (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.) Date: March 2014 This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 308363). http://www.waste2go.eu/download/1/D2.2_Waste%20profiling.pdf)

4. Balance to be converted to RDF: The design LCV is considered at 14 MJ/kg as above.

Bio-mining

300 t MSW/day will yield about 150 t of RDF. The plant fuel requirements are about 300 t/day at 14 MJ/kg LCV fuel. The balance fuel requirements will be met by bio-mining from existing waste dump of KMC adjacent (about 100 m) to the project site. The waste dump has above one million tons of high CV waste where organic material and moisture are already dried. A recovery of 85–90% of RDF is expected and about 200 t/day of bio-mining may be required in initial period. This use of existing waste—which will reduce landfill and pollution—has already been agreed with the KMC and the Government of the State of Kerala.

11.5.2.4 Waste Treatment Plant

Bio-drying

The plant is designed for 500 t/day incoming MSW.

Table 11.6 Kochi design waste: low calorific constituents and values (D 2.2 Waste Profiling, Prepared by FhG-IBP (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.) Date: March 2014 This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 308363). http://www.waste2go.eu/download/1/D2.2_Waste%20profiling.pdf)

Waste fraction	Subgroup	LHV (lower heating value) (MJ/kg)		
		Average	Min (wet)	Max (dry)
Animal and vegetable waste	Garden waste	12.5	4.8	19.6
	Kitchen waste	20.3	5.5	38.3
Household and similar waste (mixed waste)	Residual waste	12.0	4.0	20.1
	Fines	6.4	0	14.8
Non-metallic recyclables	Paper and cardboard waste	14.8	4.0	26.4
	Plastics	32.6	17.4	42.0
	Rubber	31.1	25.9	42.0
	Glass	0	0.1	0.2
	Wood	14.7	10.5	20.0
	Textiles	14.7	10.5	18.5
	Leather	15.2	N/A	N/A
Metallic waste	No subgroup	0.1	-0.1	1.4
Chemical and health care waste	Spent solvents	10.0	N/A	N/A

Table 11.7 Kochi design waste: moisture content (D 2.2 Waste Profiling, Prepared by FhG-IBP (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.) Date: March 2014 This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 308363). http://www.waste2go.eu/download/1/D2.2_Waste%20profiling.pdf)

Moisture content of some waste fractions of MSW				
Waste fraction	Subgroup	Moisture (% ww)		
		Average	Min	Max
Animal and vegetal waste	Garden waste	42	0	75
	Kitchen waste	52	0	96
Household and similar waste (mixed waste)	Residual waste	14	3	37
	Fines	30	N/A	N/A
Non-metallic	Paper and cardboard	8	0	25
Recyclables	Waste			
	Plastics	3	0	15
	Rubber	1	N/A	N/A
	Glass	2	2	3
	Wood	17	8	22
	Textiles	11	0	25
	Leather	11	0	25
Mineral and solidified waste	Ash, rock, and dirt	8	N/A	N/A

- Reception building.
  The MSW trucks are received in a covered building to control odours. The building ventilation will be closed cycle, removing odour in incoming air through wood chips to be backed by proven bio-filter system. Using this process, it is possible to almost eliminate the impact of the odour outside the building's immediate area (50 m or less). In addition, manual pre-sorting takes place by separating coarse unwanted impurities from the waste in order to protect the downstream units.
- Bio-drying Plant (see Fig. 11.24)
  The bio-drying technology selected uses naturally occurring bacterial activity. The waste is stacked in specially designed areas and covered with special membrane material that only allows water vapour to pass through it. Each stack is about 3 m high. Length and width are a function of operational convenience. The stacks are made in lanes using a wheel loader. When bacteria decompose organic matter, heat is produced as part of the metabolic activity. This basic principle is used in bio-drying. Controlled aeration, turning, etc. can improve the efficiency of and the time for drying. It is envisaged that designed drying will be achieved in about 23 day's process. Adding time for laying, removing activities, a lane (used for stacking) can be reused in about 26 days. Part recovery and relaying are also possible.

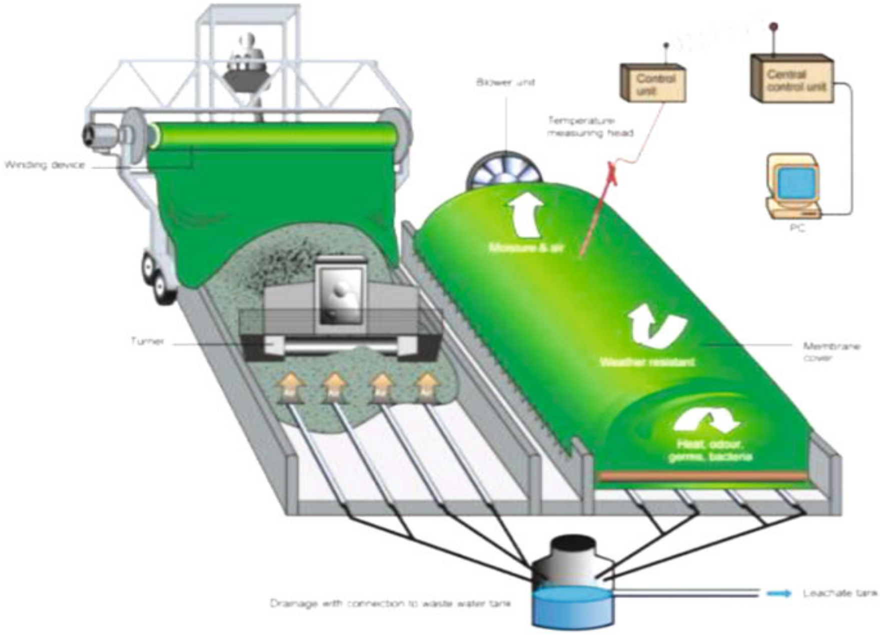


Fig. 11.24 Schematic drawing of bio-drying process (http://www.biodegma.de/windrow-composting-system.html)

- The remaining moisture as well as dry stabilized organic matter and other MSW constituents make the output material for further mechanical processing in the MRF building for RDF production.

Bio-mining Waste (BMW)

As stated earlier, about 200 t/day of waste material will be extracted from the adjoining landfill area. This material is already dry. The preparation for use as RDF comprises:

1. Shredding,
2. Screening to below 80 mm size at landfill itself and then trucked to plant MRF building.

Material Recovery Facility (MRF)

The bio-dried MSW ($\underset{\sim}{}$150 t/day) and the sized BMW ($\underset{\sim}{}$170 t/day) are taken to MRF where mechanical screening, shredding (<60 mm size), and segregation (using hand sorting, magnets, eddy current separators, etc.) processes are used for separating RDF and recovery of material like ferrous and nonferrous metals, paper, and heavy residue. The useful RDF, separated in this way, is brought to RDF bunkers.

11.5.2.5 Gasification

2 nos. 50% capacity each gasifier, working in parallel are planned.

The RDF from bunkers will be fed through a metering bin, for load control, to the sealed pressurized gasification chamber by multiple, parallel, screw conveyors. Fuel drops on to the stepped grate of gasifier which can be considered as comprising three zones. In the first zone, the fuel is dried by the radiation heat in the chamber. Its surface temperature will continue to rise until around 220–260 °C, when volatile gases will start coming out of fuel. This process is called gasification.

Small amount of air is supplied through the grate to sustain gasification process. Initial start-up will be achieved using natural gas. The fuel is heated in a combustionless gasification process at controlled temperature.

As the feed travels down to the rear part of grate, CO is also produced. The syngas comprises mainly CO and H_2 as also some CO_2 and hydrocarbons. The chars formed as a consequence of gasification process will burn out in air starving atmosphere. An undergrade ash handling system will be provided to receive any solid residue (ash) and convey it to a local container/silo.

The syngas is then led to a separate section called combustion chamber where combustion air is provided to complete combustion and convert chemical energy of syngas to heat energy.

The temperature in the combustion chambers (4 nos. per gasifier are planned: one primary and three secondary) is controlled in 900–1000 °C range by recirculation of exhaust flue gases. This high temperature is maintained for more than two seconds in accordance with EU/Indian standards to break down toxic organic compounds. Each combustion chamber outlet hot flue gases will be directly sent to a dedicated heat exchanger (Boiler) to convert the heat energy in flue gases to steam.

11.5.2.6 Power Plant

Based on the feasibility studies, the fuel analysis, the hot gases generation at gasifier, pollution control, plant availability etc. it has been decided to set up a 1 × 12.65 MW MCR Steam Turbine Generator working on 63 bar and 430 °C main steam parameters coupled with 2 × 50% Boilers (heat exchangers).

The heat exchanger (boiler) will be single drum, water tubes, and natural circulation vertical boiler. It will have three passes: first two will be empty with water wall panels and the third pass will be horizontally arranged with super heater coils and economizer. This arrangement is proposed for control of chloride corrosion. The super heater tubes are also proposed with Inconel weld built up for same reason. The boiler will operate with negative draft created by 1 no.ID fan. The boiler design and fittings will comply with IBR (Indian Boiler Regulations).

The steam turbine will be a single cylinder, non-reheat, regenerative, condensing turbine with MCR rating of 12.65 MW and VWO rating of 14.35 MW (at design back pressure of 0.1 bar abs). Two nos. uncontrolled extractions are envisaged: 1 no. LP heater and a deaerator. The condenser will be two pass divided water box type. 3 × 50% CW pumps and an induced draft RCC cooling tower will be provided. Steam jet air ejectors (2 × 100%) are proposed.

Water Systems: Raw water will be provided/pumped from Kadambrayar River, about 150 m away from the plant. An intake will be constructed at the river for this purpose. Borewells may be used to supplement the water supply as required. The plant shall be a zero liquid effluent discharge plant. All effluent will be treated and reused. Water treatment plant will comprise:

- A clarification plant
- A filtration plant comprising dual media—activated carbon ultrafiltration
- R.O. plant followed by a cation/anion/mixed bed DM plant

The WTP capacity is proposed as 5 m^3/h based on 3% system makeup.

Ash handling system: The solid precipitates from combustion process are bottom ash collected at gasifier and combustion chamber and fly ash collected at boiler and filter bags hoppers. This ash is removed from these hoppers and conveyed to a storage silo.

11.5.2.7 Pollution Control

The main objective behind a MSW based power plant is pollution control. Therefore, this aspect of the plant is most important whereas using MSW reduces the landfill requirement by over 90% but still causes emissions that would be polluting. The Government of India has laid down regulations on permissible emission limits which are compatible with EU norms. The measures proposed to control these emissions are:

1. NO_x control: For this purpose,
   (a) flue gas recirculation after boiler is used as oxygen trimmed control air released under the grate (primary air),

(b) part of flue gas is also used in the gasifier above grate to help pyrolyzation without combustion,
(c) further flue gas is recirculated through combustion chamber to control temperature and NO_x.

In addition, SNCR system using urea solution spray will be used before the flue gases leave combustion chamber to limit NOx to permissible levels.

2. SO_x Control
   Flue gases on exit from boiler will enter a reaction chamber where lime will be sprayed into the gases for precipitation of SO_x.
3. Dioxins, furons, heavy metal control:
   In the same reaction chamber, powdered activated carbon (PAC) is also sprayed to control these pollutants.
4. Particulate Matter
   The flue gases, after reaction chamber will pass through filter bags which will entrap fly ash and precipitate from the reactions to the permissible limits.
5. A CEMS (continuous emission monitoring system) will be installed near the stack to automatically adjust the ammonia, lime, or PAC dosing as required, as also purge the filter bags.

11.5.2.8 Recovered, Reusable Materials

As stated earlier, dried MSW, processed BMW are both shifted to MRF for final process. All materials not suitable for RDF are removed here. Any previous separation (as in the fuel reception building) and the ashes in the power plant are also collected at MRF. The equipment installed here in MRF will further segregate these non-fuel materials by their weight, magnetism size, etc. by suitable equipment installed here as well as hand segregation.

The final sanitized dry RDF goes to bunkers or balers. The other material will be segregated and stored in different packaging areas.

1. Some of these will be saleable items such as ferrous and nonferrous metals, glass, plastics, paper, card, etc.
2. Some like construction waste and debris can be used, along with ash produced, for making new byproducts from the waste. This can be road aggregate, blocks, tiles, etc. It is estimated that about 30 t/day of such secondary byproducts can be produced.

The leftover waste material (not suitable for recycling) will go to the landfill area. It will be ensured that this does not contain any biodegradable organic matter.

11.5.3 Turkey

Iqony Solutions GmbH completed a study for an incineration of municipal solid waste in Istanbul in 2008. As already mentioned in the previous chapters, the plant design depends strongly on the waste composition. Also the plant configuration is the same like the described plant configuration in the study of Indonesia. Out of this study, there is given a more detailed overview about the boundary conditions. The plant configuration is still the same compared to the other studies and represents a state of art for waste-to-energy power plant. It should be noted that all figures and prices in the following sections of this chapter are from 2008.

The transition from a simple waste landfill to environment useful and also expensive thermal treatment process is feasible if political basic conditions are existing, e.g. in form of laws and directives. In Germany and other European states, these laws and directives have been primarily put into force already or they are under preparation for legislation.

As thermal waste treatment is much more expensive than landfilling waste, a waste charge is considered indispensable for the generation of waste, so that an ecologically necessary thermal incineration can be financed accordingly. The main earnings to cover the investment and operating costs are the total fees to be paid by the waste supplier for delivering a waste per ton for incineration. The income from the sale of the generated energy, electricity, steam, or district heating even gains political significance in addition to the environmental aspects. However, the earnings cover only a small part of the investment and operating costs to be financed. It is not possible to finance the investment and operating costs alone by selling the generated energy.

To finance the investment and operating costs, the waste treatment fees in Germany vary at present between 100 and 350 EUR per ton of waste, depending on the kind of plant technology, plant capacity, type of waste, and local conditions. For the aforementioned waste incineration plant in Istanbul, waste treatment fees to be paid by the waste supplier to cover investment and operating costs are to be calculated.

On the assumption of 16 million citizens and an accrued solid waste of 240 kg per citizen annually, the city of Istanbul produces approx. 3,840,000 t/year, including commercial waste, e.g. from Istanbul airport. It is recommended to burn this waste quantity in four (4) plants. Due to the collection of waste and transportation distance to the incineration plants, it seems useful to erect two (2) incineration plants, each on both sides of the Bosporus' straits. For four (4) identically designed incineration plants, each plant rated waste capacity is 960,000 t/a.

Due to the waste flow rate, it is recommended to erect each waste incineration plant with six (6) incineration process lines.

When selecting the plant site, it has to be considered that the waste treatment plant is centrally located and access roads are available. Furthermore, consideration has to be given to plant sites where the generated electric energy can be fed into the national grid and eventually the possibility to supply steam or district heating, e.g. to production industries.

Due to the market situation at present in Europe, each plant erection has to be estimated with investment costs of approx. 550–600 million EUR (price status 2007) for one (1) waste incineration plant with six (6) incineration process lines and a waste incineration capacity of 960,000 t/a. Excluded in the investment costs are plot and infrastructure costs, planning costs, insurance costs, and bank charges.

11.5.4 Germany

In Germany, waste-to-energy power plants are full integrated in the power industry and have to compete on the German electricity market. Due to the increased capacities of the renewable energies (e.g. solar power, wind power) fed into the grid, the spot market prices for electricity in Germany were dramatically fallen. Sometimes the spot market price gets negative for a short period of time. Out of the effect that the main task of these incineration plants is to reduce the amount of waste, these plants are running nearly 8000 h/year at 100% capacity. The products of the water-steam cycle (energy and heat) are only byproducts because there is a so-called gate fee for the receipt amounts of waste. Consequently, waste-to-energy plants are under economic pressure due to the market price of electricity on the spot market.

Iqony Solutions GmbH has investigated whether it would be possible to increase the operational flexibility to decouple the requirements of the network operators from the generation of energy. As shown in Fig. 11.25, there are a lot of possible technical approaches to increase the operational flexibility.

Especially two possibilities were considered to be most appropriate and feasible (see Fig. 11.25, highlighted boxes). By using storage technologies, the decoupling of energy production from demand is most suitable and can be implemented to the greatest extent (compared to the other possibilities).

For heat storages there are a lot of technologies available in this case. Iqony Solutions GmbH has chosen hot water storages. The main reason for this decision is that the same heat transfer medium is used in this technology compared to district heating networks. So basically a distance heating grid is required to utilize a useful storage technology. The heat storage is a tall, isolated tank and the heat will be stored by the medium water (see Picture 11.5).

The other possible storage technology is the battery storage. Iqony Solutions GmbH has erected a battery storage capacity of 15 MW each at six locations (see example in Picture 11.6). These battery storages are mainly used for primary and secondary control power, so that the power grid can be stabilized.

The storage units are based on numerous single lithium ion-batteries cabinets.

Iqony Solutions has a detailed and long-time operating experience in both storage technologies

The following figure shows how the different storage technologies are used by the developed concept. Apart from a few other boundary conditions, the storage is primarily operated in dependence on a calculated marginal price. This marginal price is largely based on average electricity spot prices. When using a heat storage unit, there is a supply obligation towards the district heating network operator, so that a certain amount of heat must always be supplied.

The operation regime depends on a number of boundary conditions (e.g. max. storage capacity, loading capacity, discharge capacity). If the electricity price is below the marginal price, the storage is charged. If the electricity price rises above the marginal, the storage tank is discharged. As a result the energy production and the marketing of energy were decoupled (see Fig. 11.26).

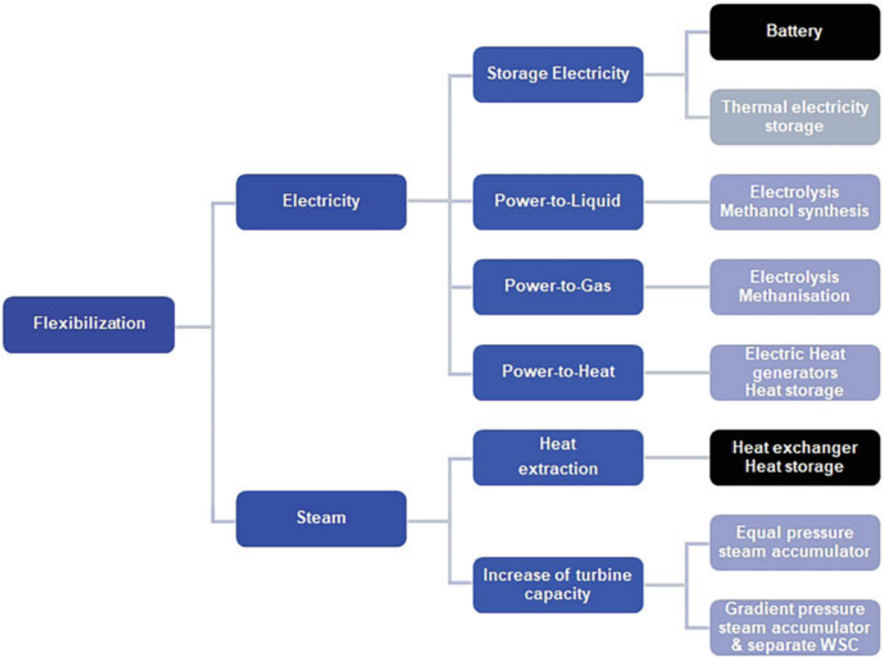


Fig. 11.25 Technical approaches to increase the operational flexibility of WtE plants

Picture 11.5 Heat storage of Iqony in the “Saar”-region

Picture 11.6 6 × 15 MW battery storages of Iqony at power plant sites

To summarize the results of the figure, it should be noted that the battery storage is used more often. However, it must be noted too that the lifetime of such battery storage units depends on the number of cycles and the electrolytes used. The heat storage is independent of the loading cycles.

From an economic point of view, however, it turned out that battery storage systems are not suitable for this application. By now the battery storages from Iqony are used to maintain network stability. The primary and secondary control services provided are remunerated separately and higher. This electricity storage application was not considered in this study, as it did not guarantee the actual purpose of this consideration. Conversely, there are economy results for heat storage depending on the storage size (see Fig. 11.27).

In Germany there is a special promotion by the so-called Kraft-Wärme-Kopplungs-Gesetz for heat storages. The aim of the German government is to reduce the CO_2-emissions and to promote the expansion of renewable energies. However, in order to be able to guarantee security of supply, storage technologies are an important component of this project.

11.6 Summary and Outlook

In conclusion the feasibility of a WtE plant is directly linked to the prosperity and the development stage of the project country.

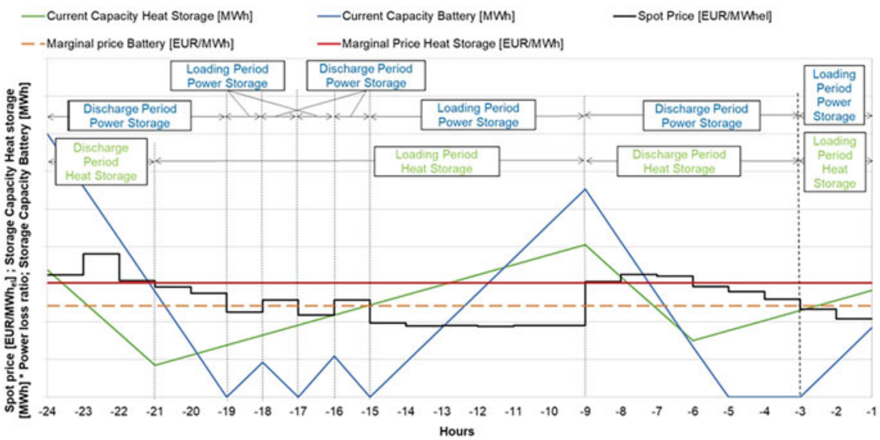


Fig. 11.26 Operation mode of the heat storage and the battery depending on the limit price (Konzeptentwicklung zur bedarfsgerechteren Strom- und Wärmeauskopplung von Müllheizkraftwerken unter Einbindung von verschiedenen Speichertechnologien, Dr. Nolte, Mr. Lagodny)

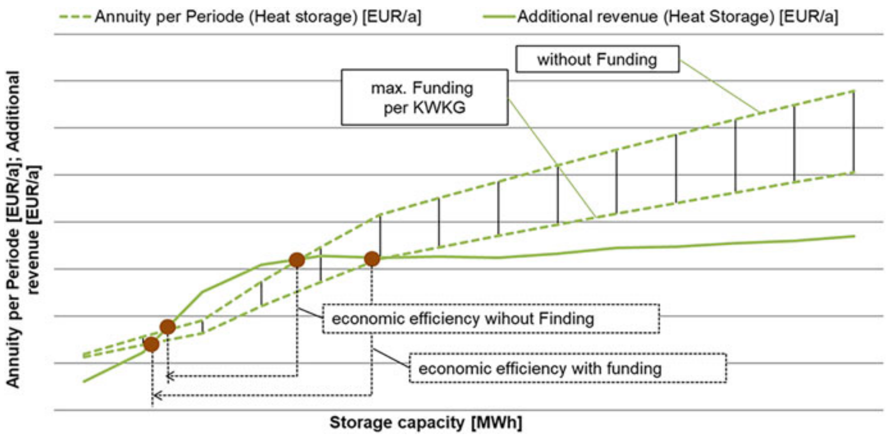


Fig. 11.27 Economic efficiency analysis for heat storages (Konzeptentwicklung zur bedarfsgerechteren Strom- und Wärmeauskopplung von Müllheizkraftwerken unter Einbindung von verschiedenen Speichertechnologien, Dr. Nolte, Mr. Lagodny)

Firstly the ultimate benchmark is 40 EUR per ton of waste, which needs to be raised by the community by whatever instrument. Secondly the supply chain has to be secured by amount and price. Finally a WtE project is also “just” a normal energy project.

Beneath these circumstances the social factor around the informal recycling has to take into account discussing the impact of such a plant.

It must also be stressed that there are a number of good reasons, such as the protection of the environment, in particular the soil and groundwater, and the use of energy content. Although large-scale WtE plants are quite rare in India due to the reasons described above.

As shown in the specific case studies each country has its specific boundary conditions, which are crucial for the economic efficiency of the waste incineration plant and for the success of the investor as well as the operator. Therefore a general approach and globally applicable benchmark for a specific technology for each WtE plant could not be adopted for potential sites and countries. A case-by-case evaluation should always be the most appropriate method.

Last, but not least waste to energy, i.e. waste incineration, plays an important role in circular economy in treatment of discharges of the circle. In the future, the circles of biological and technological material, as shown in Fig. 11.3, must be significantly improved, and the amount of material discharged (“waste”) will hopefully be less than today. But this circumstance makes the importance of waste to energy even more important to protect the environment.

Utilization of Household Sewage Sludge as Resource: The Effect of the Temperature of Pyrolysis on the Chemical Properties

12

Jozsef Kovacs and Sadhan Kumar Ghosh

Abstract

The world's attention is currently focused mostly on worries about harmful changes to the physical, biochemical, and microbiological qualities of air, water, and soils, which influence human, animal, and plant life. Sludge from wastewater treatment plants has been described as a potential sustainable energy source and material recovery. Sewage sludge needs environmentally safe utilization, its nitrogen, phosphorus, and potassium content. The purpose of this research paper is to present the obstacles due to the residual heavy metal content of sewage sludge, where the conversion by pyrolysis into biochar is a promising alternative. This paper demonstrates the effect of pyrolysis temperature in order to create biochar that can be used as a soil fertilizer. Since the use of produced biochar is critically affected by heavy metals (e.g., Pb, Cr, Cd, Cu, and Zn) this paper investigates the effect of pyrolysis of sewage sludge at different temperatures (300 °C, 450 °C, and 650 °C). The agronomic potential of biochar is examined based on nutrient content (TOC, TN, P, and K). The effect of the pyrolysis temperature on the concentration of heavy metals showed a lower level in the case of biochar produced at 450 °C as a result, it is the recommended pyrolysis temperature. Practical implications are manifested in that the pyrolysis of sewage sludge is an alternative method to recycle the nutrients of sewage, therefore it be an environmentally friendly option ensuring the nutrient cycle. Social implications of the paper are not negligible as the growing amount of

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sewage sludge needs environmentally safe utilization, its nitrogen, phosphorus, and potassium content must be recirculated into the soil as part of the bio-geochemical cycle. Considering the originality, it is recommended to carry out further examination of chemical residues remaining in the biochar, and the fact of the decomposition of microplastics must be confirmed in the future.

Keywords

Pyrolysis · Household sewage sludge · Heavy metals · Biochar · Circular economy · Waste water treatment · Soil fertilizer

12.1 Introduction

In removing the suspended solids from waste water and conversion of organic soluble compound to bacterial biomass, sewage treating plants produce a semi-solid substance known as sewage sludge (Wang et al. 2013; Kumar et al. 2017). The growing amount of sewage sludge is causing more problems, the solution of which cannot wait, since the amount of sewage sludge is constantly increasing. The safe and environmentally safe disposal of sewage sludge generated during the process of sewage treatment is an important task. In addition to the nitrogen, phosphorus, and partly potassium active substances, municipal sludge provides micronutrients, and there are many methods for their treatment.

On the other hand, the intensive cultivation accelerates the nutrient depletion rate from the soil, leading to the depletion of native fertility status, which is emerging in deficiency or lack of soil organic carbon. As in many countries, the shortage of macro- or micronutrients occurs in soil up to a threat level, more attention should be paid to managing soil fertility and recycling the soil wastes generated in urban areas to overcome this problem (Krishna et al. 2021). It has been observed that the sewage sludge may be a source of fertilizers that could improve soil fertility and productivity due to an array of nutrients and organic matter, however, the presence of heavy metals in sewage sludge is a matter of concern. The utilization and disposal of sewage sludge by composting is one of the possible and most widely used solutions to the aforementioned problem of the sewage sludge generated. In addition to plant nutrients, the by-products used as carbon sources and additional micro- and macro-elements, as part of the bio-geochemical cycle. The conversion of domestic sewage sludge by pyrolysis into biochar and additional energy products is a promising alternative for reducing the amount of domestic sewage sludge and at the same time using the biochar as soil fertilizer.

Sewage sludge management is important for avoiding emissions and mitigating negative effects on the atmosphere, human health, and long-term development. Cities generate hundreds of tons of waste annually, the bulk of which is sewage sludge, as the global population expands, and urbanization occurs. The effect of physical parameters of pyrolysis, such as temperature, on the released products and energy recovery has been extensively studied, in this context there is little information on plant nutrient recovery and on the heavy metal content of biochar and the resulting potential toxicity prior to reuse as a soil amendment.

This study investigates the ideal pyrolysis temperature based on literature and primary research by measuring different input and output parameters. The quality parameters of the biochar produced as an output of the pyrolytic process ensure quality standards for land placement, highlighting the importance of toxic heavy metals. This study also investigates the effect of pyrolysis temperature (300, 450, and 650 °C) on the characteristics of mixed, desiccated sewage sludge collected from urban sewage treatment plants. The study results will help enhancing the recirculation of sewage sludge. If the biochar produced does not meet the requirements, its use is only possible as an energy source (burning, co-incineration). It can be seen that this only results in a quantitative reduction of the treated sewage sludge, it involves the use of fossil energy carriers and emissions, and does not ensure the circular processes, the recirculation into the Earth's geochemical system. In order to do this, it is necessary to check compliance considering the relevant operating conditions, e.g., at selected pyrolysis temperatures, taking into account the heavy metal content of the biochar.

Measurements were not conducted related to the analysis of the composition of the liquid and gaseous products generated during the pyrolysis experiments, which researches are planned to be dealt with later. In this matter, until the measurements are carried out, relaince of the study is more on the literature. The temperature has a significant effect on the physical parameters of pyrolysis, and the characteristics of biochar. Biochar produced at low temperature shows higher volatile organic matter (VOM), TN and P content, however, higher pH, EC, Na, and K were found in biochar produced at higher temperature.

The purpose of this paper to provide an answer to the question, if there is a parameter among the physical parameters of pyrolysis that affects the remaining heavy metal content, as a critical characteristic of biochar? If so, what happens if the physical parameters of the pyrolysis are set not for the purpose of optimizing the output product, but for aiming the minimum heavy metal content of the biochar?

The volatile organic matter (VOM), mineral content (MC), plant nutrient content (total nitrogen, available phosphorus P and potassium K), alkalinity (pH), salinity (electrical conductivity EC and Na) have to be addressed during the conversion of raw sewage sludge by pyrolysis and the analysis of the generated biochar. Since the use of biochars from sewage sludge is critically affected by traces of heavy metals (e.g., Pb, Cr, Cd, Cu, and Zn) due to their toxic effect, finding related literature sources with applicable technical background was also important to measure toxicity.

12.2 Situation Report

The process of Waste water treatment is the basis for improving the quality of aquatic ecosystems, the safe drinking water base and also affects the economic activities related to aquatic ecosystems. By the way, it is impossible to ensure safe

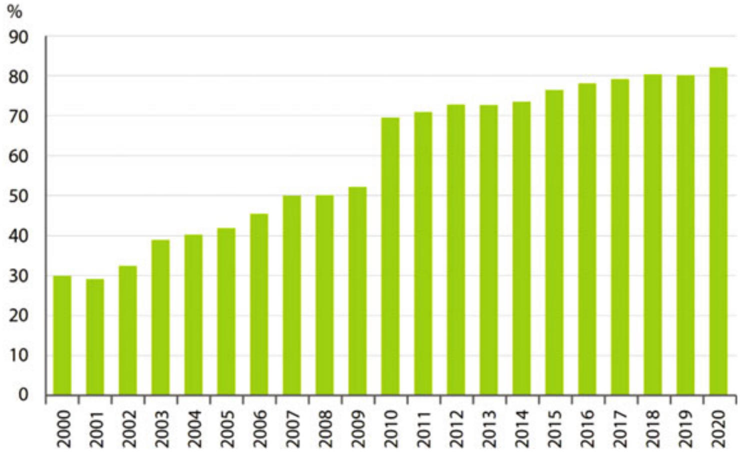

Fig. 12.1 The estimated proportion of the population connected to at least II. purification grade (biological) waste water treatment plants in Hungary (Central Statistical Office 2020)

public health conditions without Waste water treatment. After the appropriate Waste water treatment procedure, the pollution below the limit value remaining in the water is broken down by the self-cleansing ability of the receiving natural water, so that further use of the water is possible, and the original, natural water quality state is not significantly damaged.

The increasing amount of residual municipal sewage sludge is causing more and more problems. An environmentally friendly solution to the treatment, processing, and disposal of waste is an important task, since the amount of sewage sludge is constantly and significantly increasing.

The reason behing this tendency is not only a technological issue, but basically the higher number of the properties connected to the Waste water treatment plants. The size of this population has increased 2.5 times since the 2000s (Fig. 12.1), which is basically was related to the implementation of the waste water drainage and cleaning, the most significant development need among Hungary's tasks related to the European Union membership. The European Community defined the treatment of urban waste water in Directive 91/271/EEC. It prescribed the collection and cleaning of urban waste water as a mandatory task for the member states above a pollutant load of 2000 population equivalents (PE), and also defines the concepts to be used for uniform implementation.

Hungary implemented the tasks in the National Urban Waste water Drainage and Cleaning Implementation Program, which is based on the decree 5/2002. (II. 27) government decree (Hungarian Government Decree No 50/2001 n.d.). Its implementation was facilitated by several national development programs (environmental operative and development programs).

The positive effect of the implementation of the EU Urban Waste water Treatment Directive on urban waste water treatment is clearly visible in the figure above (Fig. 12.1). In 2020, at least II. The proportion of the population connected to

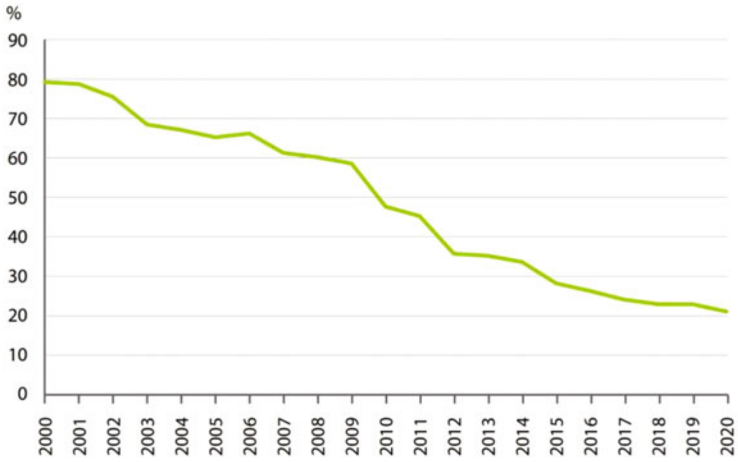

Fig. 12.2 Hungary's municipal waste water treatment index between 2000 and 2020 (Central Statistical Office 2020)

(biological) Waste water treatment plants was 81%, which is primarily due to the commissioning of the new central sewage treatment plant in Budapest, handed over in 2010, and the new or improved plants that have been put into operation since then (Central Statistical Office 2020).

Hungary's Waste water treatment index (2020-ban 23.1%, Fig. 12.2) is considered favorable in Europe; not so long ago, among EU member states, only the Czech Republic and Estonia had a more favorable indicator value. The reason for the differences between the countries is primarily the different levels of water utility equipment of the apartments in each region and the Waste water drainage and cleaning technology used (Central Statistical Office 2020).

12.3 Water Pollution

At the end of the treatment, the purified Waste water discharged from the Waste water treatment plants is sent to a receiver, typically surface watercourses. Therefore, it is important that the parameters of the treated Waste water discharged from the Waste water treatment plants do not exceed the limits prescribed by "Decree of the Ministry of Environment Protection 28/2004. (XII. 25.) on limit values for emissions of water pollutants and some rules for their application."

This means that, e.g., nitrogen and phosphorus in treated Waste water should not cause eutrophication when they enter our natural waters. The five-day biochemical oxygen demand (BOD5) load of the discharged, treated Waste water can destroy the oxygen balance of the receiver, which is also harmful to aquatic ecosystems.

Data on Waste water treatment are available on the website of the Central Statistical Office, but they are of a statistical nature, the annual average nitrogen,

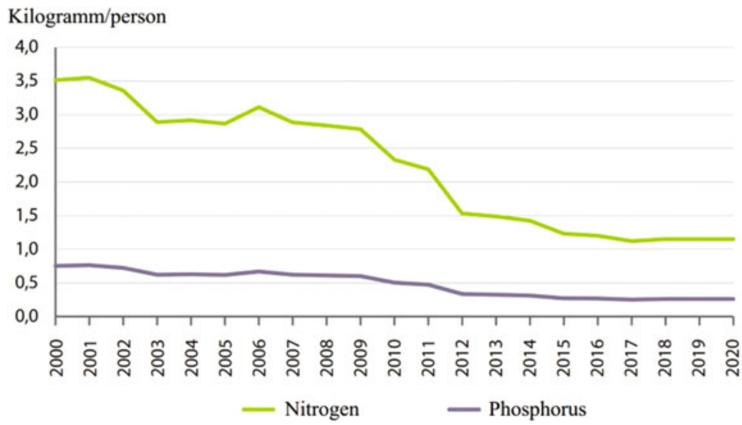

Fig. 12.3 Estimated annual nitrogen and phosphorus emissions of households after Waste water treatment in Hungary (Central Statistical Office 2020)

phosphorus, and five-day biochemical oxygen demand (BOD5) loads after cleaning from households can be estimated from the basic data of statistical surveys (Fig. 12.3).

The diagram of estimated annual nitrogen and phosphorus emissions of households for the period 2000–2020 shows the average annual nitrogen and phosphorus load after waste water treatment according to Central Statistical Office's data. The emission data was calculated by Central Statistical Office from the estimated data of the population living in households connected to the Waste water treatment plant, with the following specific emission factors before the annual cleaning:

- nitrogen emission factor: 4.4 kg N/person;
- phosphorus emission factor: 1.0 kg P/person.

12.4 Sewage Sludge

In Hungary the concept of sewage sludge is defined in the regulation governing its use (this is Government Regulation (50/2001 (IV.3) and FVM Regulation 36/2006 (V. 18)), and "sludge" and "Government Decree" 50/2001 (IV.3.)) also distinguishes between the concept of "sewage sludge" (Hungarian Government Decree No 50/2001 n.d.). It should be noted that the decree of the Ministry of Agriculture and Rural Development highlights sewage sludge from the waste circle and characterizes it as a raw material for compost, but only in this case, if according to the decree by observing certain parameters, with appropriate composting technology, it can be declared as a ready, saleable product, as a yield-enhancing preparation, i.e., as "product compost".

According to the wording of the decree, “Sludge is defined as sludge generated during the treatment of municipal sewage and from other sewage treatment plants and sewage treatment equipment that treat sewage with a similar composition, and municipal liquid waste” (Hungarian Government Decree No 50/2001 n.d.).

This decree also defines the definition of “treated sludge, i.e., sewage sludge,” according to which biological, chemical, heat treatment or other processes, such as the production of biogas from sewage sludge in particular, as well as long-term storage or chemical treatment of liquid municipal waste for at least 6 months sludges whose pollutant content does not exceed the values specified in the decree (Hungarian Government Decree No 50/2001 n.d.). It should be mentioned here that the regulation also determines the amount of Fecal Coli and Fecal Streptococcus measured in ml of sludge as a result of the treatment, which cannot exceed 10% of the original value.

Waste water treatment as a technological activity ensures differences in input and output parameters. The technology is mainly aimed at removing organic materials, nitrogen and phosphorus-containing compounds, one of its by-products is residual sewage sludge. The placement of this is a constantly present and growing problem, but with a suitable solution and alternative recycling technology, it can even represent another opportunity.

It has been observed that the pollutants remaining in sewage sludge are reduced to a fraction of the inputs. It can also be seen that the organic matter content of the outputs, even if they meet the regulatory limits, is still high.

By extracting, recycling, and returning this residual organic matter content to the Earth's geo-biochemical cycle, it represents a serious value. For agriculture, organic materials, plant nutrients, materials that can be easily used, and as by-products or secondary raw materials serve as raw materials for other products. In the case of agricultural utilization of sewage sludge, it is also important that the nutrients are not only “there,” but also accessible, in as large a proportion as possible. It is not incidental that the presence of other substances permitted by regulation, such as heavy metals (and, for example, toxins, pathogens, other organic pollutants) should be minimal. The composting process is able to keep all of this at the expected and permitted level, and control it chemically and biologically.

12.5 Main Parameters of Sewage Sludge

In Hungary, the “open utility scissors” was a well-known phenomenon, that is, the phenomenon when the sewer network for the disposal of municipal waste water via public sewers—which at the beginning of the 1990s was significantly behind that of developed European countries—and the ratio of properties connected to the drinking water supply we take it. The question was rightly raised that if the supply in the case of connected apartments barely exceeded 40%, where did the waste water go—and the answer was that more than 50% of the waste water went into the receivers without being cleaned.

In the case of sewage sludge, we can rely on the following sources for data:

Table 12.1 The trend of the generated sewage sludge in Hungary (Zöldi 2015)

Year	Load (residential equivalent—RE)	Originated quantity (t dry material/year)
2013	8,750,148	179,378
2016	10,992,712	225,351
2023	11,603,418	237,870
2027	12,214,124	250,390

- Municipal waste water Information System ("TESZIR"): OSAP no. 1376 data collection (basis of the national Waste water program according to Article 16 of Directive 91/271/EEC), with online option
- Central Statistical Office—National Statistical Data Collection Program (OSAP): OSAP no. 1062 data collection report on the drinking water supply, sewage disposal and Waste water treatment of settlements (it contains data from 782 sewage treatment plants (for 1857 settlements)
- Waste Management Information System (HIR): the online file contains the data of 370 sites (since there are 782 sites, the database only contains less than half of them)

With the implementation of the National Waste water Drainage and Cleaning Implementation Program between 2004 and 2015, the number of residents living in the area with a sewage collection sewer network in the country will increase from 68% to 91%, and the total amount of Waste water collected with the collection network will receive at least second-degree biological treatment before discharge into the receiving water. Altogether 665 settlements were affected by the construction of a new collection system, while 1068 settlements were affected by the expansion of existing systems (Tomócsik 2021).

Waste water treatment rates have now improved, and in 2005 the proportion of apartments connected to the sewage network was already 65%. As a result of improvements to the Waste water treatment plant, the proportion of biologically treated Waste water increased from 61% to 66% between 2002 and 2005, within which the 3rd stage of purification (nitrogen and phosphorus removal) increased from 20% to 30% (Tomócsik 2021).

In connection with sewage canalization, the volume of sewage treatment increases, which increases in proportion to the amount of "by-product" formed during cleaning, the amount of sewage sludge. Currently, approximately 100–120 thousand t/year of dry sludge is produced in Hungary, which is expected to triple by 2025 (Zöldi 2015) (Table 12.1).

Sewage sludge is a by-product of Waste water treatment technology and appears in several places during the technology. The amount of sludge separated in the process is 0.5–1.0% of the volume of the received Waste water in the case of a modern Waste water treatment plant (Tomócsik 2021). Raw sludge also comes from the pre-sedimentation unit, which has a very high moisture content (92–95%), and the moisture content of the excess activated sludge is slightly less than this (96.5–98.0%). After digestion and dewatering, the sludge naturally loses a lot of its moisture content (dry matter content is between 6 and 12%), and the organic matter content also increases (30–60%) (Tomócsik 2021).

12.5.1 The Nitrogen

The following chapters review data on the nutrient content of sewage sludge, starting with nitrogen first.

Nitrogen (N) occurs in both mineral and organic forms in sewage sludge. Water-soluble ammonium-N can be taken up directly, but in the case of nitrogen bound in organic compounds, a retention effect can be expected. The utilization of organic N depends primarily on the biological degradability of the organic material and its C/N ratio. The degradability of organic matter is significantly higher in the case of aerobically stabilized sludge than in the case of digested sludge (Tomócsik 2021) (Table 12.2).

12.5.2 The Phosphorus

Phosphorus is also present in sewage sludge in two main forms. One form is present in the organic bond, the other is present in the inorganic form (phosphate). The amount of both forms depends on the used Waste water treatment and sludge treatment technology, in a three-stage Waste water treatment plant, the phosphorous content of the resulting sludge is higher than without chemical phosphorus removal. Apart from the amount of phosphorus, its availability is also important. This is determined not only by the chemical form in the sludge, but also by several factors, such as the soil chemistry, lime and clay content. However, the literature is unanimous in that sludge can be considered a complete source of phosphorus.

12.5.3 Potassium, Calcium, Magnesium

The potassium content of sewage sludge is usually low. The doses of sludge used in practice usually do not satisfy the potassium needs of the cultivated plants, therefore additional potassium fertilization is necessary when sewage sludge is used (Tomócsik 2021).

Table 12.2 The average nutrient content of municipal sewage sludge in Hungary (Tomócsik 2021)

The average nutrient content of municipal sewage sludge		
Nutrient	Tested sample (cs)	% in dry matter
N	6289	3.84
P2O5	6014	3.65
K2O	5863	0.42
MgO	5859	0.97
CaO	6141	7.37

The calcium content of sewage sludge does not directly influence the nutrient absorption of plants, but indirectly by improving the physical and chemical properties of the soil. The calcium content of sludge largely depends on the used sludge treatment technology (e.g., stabilization with lime dosage) (Tomócsik 2021).

Plants have a high demand for magnesium: after the three macro-elements (nitrogen, phosphorus, and potassium), magnesium is next in line. Without magnesium, there is no photosynthesis, and it also plays an important role in transporting the produced assimilates to the right place (e.g., in the root system, in the fruit). There is minimal literature available on the magnesium content of sludges, but since magnesium is present, sewage sludge usually provides the magnesium supply to cultivated plants.

12.5.4 Microelements

Sewage sludge contains different amounts of essential microelements (Mn, Zn, Fe, Cu, Mo, and B) needed by plants. However, the utilization of these elements does not primarily depend on the content of all microelements in the sludge, but on the soil properties that influence their absorption (Tomócsik 2021).

12.6 Risks of Disposal of Sewage Sludge

In addition to the useful plant nutrient content of sewage sludge, the risks of sludge disposal must be taken into account. Large amounts of phosphorus and nitrogen from sewage sludge can also promote eutrophication of surface waters. Due to the placement of a large amount of sludge, nitrate can accumulate in the soil profile and leach into the groundwater. Sewage sludge contains heavy metals and organic toxic compounds to varying degrees, which can accumulate in the soil if used improperly and enter the food chain through the soil–plant system (Tomócsik 2021).

The agricultural use of sludge is always carried out through the mediation of the soil. With the help of micro- and macroscopic organisms living in the soil, the material transformation processes that lead to the breakdown, transformation and recycling of the components of sewage sludge entering the soil take place (Tomócsik 2021).

The soil, mainly thanks to its clay content, has a buffer capacity against various pollutions. However, topsoil is our natural resource that is only available to a limited extent, which is also protected by law, therefore all soil-related activities must be carried out in such a way that it does not cause damage to the soil's natural system. The disposal of sewage sludge for agricultural purposes can therefore only be carried out under strict control, in compliance with the prescribed registration obligation, and in possession of an official permit (Tomócsik 2021). In Hungary the agricultural disposal of untreated sewage, raw sludge, and untreated sludge is prohibited. Furthermore, the agricultural use of sewage sludge in which the concentration of

Table 12.3 Concentration of toxic elements or harmful substances (limit values prescribed in Annexes 3–5 of Government Decree 50/2001 (VI.3) (Hungarian Government Decree No 50/2001 n.d.)

Permissible concentration of toxic elements and harmful substances in soils according to Annex No. 3 of 50/2001. (IV. 3.) Government decree on the rules for the agricultural use and treatment of waste water and sewage sludge		Limit values of toxic elements and harmful substances in sewage sludge for agricultural use according to Annex No. 5 of 50/2001. (IV. 3.) Government decree on the rules for the agricultural use and treatment of waste water and sewage sludge	
Parameter	Limit values (mg/kg dry material)	Parameter	Limit values (mg/kg dry material)
As	15	As	75
Cd	1	Cd	10
Co	30	Co	50
Σ Cr	75	Σ Cr	1000
CrVI	1	CrVI	1
Cu	75	Cu	1000
Hg	0.5	Hg	10
Mo	7	Mo	20
Ni	40	Ni	200
Pb	100	Pb	750
Se	1	Se	100
Zn	200	Zn	2500
Σ PAH	1	Σ PAH	10
Σ PCB	0.1	Σ PCB	1
TPH	100	TPH	4000

toxic elements or harmful substances exceeds the limit values in annex No. 5 of Regulation 50/2001 (VI.3.) Government Decree is prohibited (Table 12.3).

The amount of sewage sludge produced in the biological treatment unit of sewage treatment plants can be determined by considering the corresponding amount of liquid sludge as one hundredth of the annual or daily sewage volume, with an average dry matter content (Tomócsik 2021).

12.7 Treatment and Resource Circulation: Sewage Sludge

The purpose of sewage sludge treatment is to reduce the moisture content of the material, to reduce or eliminate odour damage and infectiousness in order to place and utilize it.

These properties and environmental protection and public health problems of the resulting sewage sludge are closely related to the treatment method. The most critical factor of the entire Waste water treatment technology is the placement and utilization of the generated sludge (Tomócsik 2021).

When determining sewage treatment methods, attention must always be paid to the placement of sewage sludge. The quality of the treatment technology depends on the most critical part of the process, i.e., the placement and utilization method, as well as the composition of the incoming Waste water (Fig. 12.1).

The quality of sewage sludge is specific to the given settlement, mostly to the cleaning technology, and thus can vary from settlement to settlement. These factors influence the subsequent use. Improving the efficiency of cleaning technologies and increasing the number of stages usually leads to an increase in the amount of sludge (Tomócsik 2021).

More important procedures for sludge treatment and disposal:

- sludge stabilization,
- sludge thickening,
- conditioning,
- sludge disinfection,
- composting, extraction of biogas,
- dewatering, drying,
- composting,
- energy utilization,
- incineration/co-incineration,
- disposal, landfilling.

The disposal of sewage sludge produced in municipal and industrial sewage treatment plants is problematic for several reasons. First of all, the amount of sewage sludge is constantly increasing by 210 million. Secondly, the purpose of the technology is to purify the water, therefore the substances, heavy metals, etc. removed during the decontamination processes. Most of it appears in sewage sludge, concentrated due to cleaning.

The treatment of sewage sludge is complicated and inevitably causes additional pollution. Thus, composting, agricultural use of sewage sludge, disposal, and incineration, which are the most common ways of removing sewage sludge, do not eliminate the environmental burden, and are still a significant source of risk. Despite the restrictions set out in the decree (e.g., the amount of application in nitrate-sensitive areas can be no more than 170 kg/ha of nitrogen active ingredient per year), the intensive agricultural use of sewage sludge leads to an increase in the concentration of heavy metals in the soil (Tomócsik 2021).

This paper will not go into the presentation and characterization of the individual processes, it will only present the most representative form of utilization in our country, composting, in detail.

12.7.1 Composting

In this chapter, I briefly describe the compost production process of the sewage sludge used in the experiment, according to the case study at the central composting plant of “Green Border” Composting Nonprofit Ltd. (settlement of Érd, Hungary). The amount of different materials (e.g. basic-, supplementary and additive materials) used in the technology applied at the compost plant is determined by the product to be generated.

The Composting Plant of settlement of Érd, Hungary was built in 2015 with funding from the European Union funds. Its experimental technological development was carried out with the support of the Norwegian Fund by the owner of the site, Érd County City. Érd currently produces nearly 10,000 tons of compost per year.

The “Green Border” Composting Nonprofit Ltd. has two approved compost recipes:

- municipal sewage sludge, 50 m/m %;
- green waste from residential and public area selective collection, 50 m/m %.

The compost made az the settlement pf Érd received a product license under the name “Premium Green Border Compost” in 2019. The other product is “Premium Green Border Worm Mold,” which is a vermicompost, the highest quality compost, the enzymes and beneficial bacteria cultures produced by earthworms enhance the benefits of compost. This “earthworm mold” is the kind of compost that is closest to nature, since for its production they use earthworms that also occur in nature.

In the technology, as the first step in the production of prisms (depending on the recipe), biomass, green waste, straw, and/or chopped wood shavings shredded with a shredder are spread on the prism base. This is followed by the application of the digested sewage sludge to the spread structuring material, using a container transport vehicle or a front loader from the temporary storage. Another layer of shredded straw and mud is added to the spread mud in several passes, and then the layered prism is mixed. The prisms are compacted and aligned with a front-loading machine.

The compost conforming to the composition stated in the permit is sifted before sale, the sifted compost is then packaged and sold, which is (unfortunately) mainly used for grassing highways, preferably in planting pits when planting orchards, and only rarely for supplementing nutrients in field crops.

12.7.2 Test Parameters of the Compost Mixture

The composition of sewage sludge compost is regulated by the currently valid 36/2006. (V.18.) It was compiled in compliance with the limit values of the Ministry of Agriculture and Rural Development regulation for composts. Prior to use, the raw materials used for the production of compost are inspected by the Pest County Government Office PE-06/KTF/02070-2/2020 was determined in the waste management license issued under case file no. The quality parameters of the produced compost are continuously measured, and summarized (averaged on an annual basis) I present them in the following Table 12.4 during the examined period 2019–2021.

Table 12.4 The quality parameters of "Green Border Compost"

Parameter	Year examined			Prescribed limit value
	2019	2020	2021	
Dry matter content (m/m% original material)	58.8	52.6	517	50>
Organic matter content (m/m% dry matter)	26.8	27.1	24.7	25>
Density (kg/dm^3)	0.89	0.9	0.9	<0.9
pH (H_2O)	7.55	7.62	7.37	7.55 ± 0.5
Total water-soluble salts (m/m% solids)	0.31	0.28	0.22	<4.0
Total N content (m/m% dry matter)	1.19	1.16	1.20	1.0>
Total P_2O_5 content (m/m% dry matter)	2.57	2.69	2.55	0.5>
Total K_2O content (m/m% dry matter)	0.56	0.46	0.59	0.5>
Total Mg content (m/m% dry matter)	0.57	0.66	0.63	0.5>
Total Cs content (m/m% dry matter)	1.42	1.22	1.27	1.2>
As (mg/kg)	8.04	8.99	9.12	10.0
Cd (mg/kg)	1.74	1.95	1.63	2.0>
Co (mg/kg)	7.61	8.75	8.91	50.0>
Cr (mg/kg)	27.90	31.17	12.41	100.0>
Cu (mg/kg)	104.63	122.81	84.67	300.0>
Hg (mg/kg)	0.65	0.86	0.72	1.0>
Ni (mg/kg)	28.10	24.87	36.19	50.0>
Pb (mg/kg)	26.53	22.49	26.82	100.0>
Se (mg/kg)	0.93	0.58	1.37	5.0>

Table 12.5 Ministry of agriculture and rural development decree for composts (Hungarian Government Decree No 50/2001 n.d.)

Parameter	Year examined			Prescribed limit value
	2019	2020	2021	
Total PAH content (19 compounds) (mg/kg) dry matter	–	–	–	1.0>
Mineral oil content (TPH C5-C40) (mg/kg) dry matter	–	–	–	100.0>
Total indicator PCB content (mg/kg) no. (sum of PCB-28, 52, 101, 118, 138, 153, 180)	–	–	–	0.1>

The compost parameters are constantly measured, but I did not receive data for the following parameters in City of Érd, however, the compost composition of the sewage sludge is determined by the currently valid 36/2006. (V.18.) I present it in accordance with the limit values of the Ministry of Agriculture and Rural Development regulation for composts (Table 12.5).

12.8 Pyrolysis

Disposal is very far from circular processes, does not meet the criteria for replacing organic matter, requires a lot of space, and transport costs are high. Expensive equipment must be installed in waste incinerators to prevent the emission of gases and solid pollutants.

Pyrolysis offers an alternative to this. In view of these disadvantages, pyrolysis of sewage sludge is currently being investigated at several levels as an alternative to the disposal problem of sewage sludge. Pyrolysis has certain advantages over other methods (Basu 2010). The volume of the solid residue is drastically reduced; the heavy metals present in the carbonaceous matrix are relatively resistant to natural leaching, creating gases and oils with a high specific energy value, which can be used as potential fuels. The energy requirement of pyrolysis is lower, since it takes place at a lower temperature than in the case of burning, which limits the amount of pollutants released in the pyrolysis gases, and since the process takes place in the absence of air, no dioxins are produced (Inguanzo et al. 2002).

However, the pyrolysis of sewage sludge is not without disadvantages. It is a fact that the reduction of solid residues is lower than with incineration, and when the energy products (heating gases and/or liquids) produced during pyrolysis are burned, gases containing harmful compounds are produced. The technology of using pyrolysis is still less developed than that of incineration, the number of industrial-scale equipment is negligible. The use of pyrolysis is supported by many technological developments (Basu 2010).

The number of available research dealing with different aspects of pyrolysis of sewage sludge examines technological solutions, parameters, and material combinations. Research analyzes continuous and batch technologies, rotary kilns, fluidized bed solutions, and fast pyrolysis (Basu 2010). In addition to these, the economic aspects of the various pyrolysis processes must also be studied. In this, it is also important to investigate (parameter optimization) the pyrolysis of sewage sludge under different conditions to study the mechanism of pyrolysis and/or the characteristics of gases, oils and tars, and solid residues (Inguanzo et al. 2002).

The aim of this chapter is to gain more insight into the effect of different pyrolysis conditions (temperature and heating rate) on the main characteristics of the gas, liquid, and solid fractions produced during the processing of sewage sludge from municipal sewage treatment.

12.9 The Possibility of the Application Circular Economy in Practice

The aim of the Circular Economy (CE) is to achieve sustainable development, with the responsible and cyclical use of resources, in order to maintain its economic value and at the same time minimize the burden on the environment. Pyrolytic biochar systems utilizing the residue of municipal water purification offer an opportunity for the practical application of the CE model. The utilization of municipal sewage sludge by pyrolysis, i.e., in practice the production of biochar from sludge, is a complex, multi-output system that focuses on the production of biochar, but also produces several (bio)energy products. In addition to sludge, a wide range of other biomass raw materials can be used as input, including food waste, green waste, animal waste, and biowaste from food processing. The various (bio)energy products ensure the process's own energy needs, so we can speak of a self-sustaining process that does not require the use of fossil energy sources.

The production of biochar and mixing it with soil can be a means of sequestering atmospheric CO_2. In this way, the production of pyrolytic biochar can contribute to mitigating climate change. The produced biochar can be used widely, its basic purpose is agricultural soil improvement, but it can also be used in the technology of wastewater treatment, cement production, and also during the remediation of contaminated soils. This versatility of biochar systems creates great opportunities for the development of circular models of waste management, which are capable of transforming various waste streams into materials and even marketable products.

The practical example of CE is the Serbian research and development project of Openware-SBS Research and Development Investment and Operator Ltd. Is to produce the highest possible amount of biochar using sewage sludge. Under the current technical conditions, there is no possibility of further technological use or sale of liquid or gas products. The primary use of the liquid and gas products produced during the process is possible as energy products, integrated into the local energy consumption process, reducing fossil fuel consumption.

The primary aim of research and development project is to profitably produce biochar , which will be used as a soil amendment and fertilizer as a product. Changes in nutrient status, salinity, and metal content of the biochar define the purpose of the use and the possibility of recycling. Biochar as a fertilizes has many are specific expectation, both in terms of content and regulation.

If the biochar produced does not meet these requirements, its use is only possible as an energy source (incineration, co-incineration). It can be seen that, from those who believe that this only results in a quantitative reduction of the treated sewage sludge, it involves the use of fossil energy carriers and emissions, and does not ensure the circular processes, the recirculation into the Earth's geochemical system. In order to do this, it is necessary to check compliance considering the relevant operating conditions, e.g., at selected pyrolysis temperatures, taking into account the heavy metal content of the biochar.

Life cycle assessment (LCA) methods have been used by many authors in the literature to evaluate and compare the environmental effects of biochar production with other, the so-called traditional, technologies. Based on these studies, it is recommended to continue this work, in professional areas such as the critical analysis of the LCA of biochar production from different sources, using different technologies, and producing different output products. These studies use a "cradle to grave" method and reveal serious differences in the relationships and characteristics of the processes.

By combining life cycle assessment (LCA) and circular economy modelling, it has been proven that the use of biochar is a very promising way to contribute to carbon dioxide-efficient resource circulation, climate change mitigation, and economic sustainability, but further modelling is recommended taking into account parameters such as the heavy metal content of the biochar, the usability of the energy products produced during pyrolysis, the role of the catalysts used in the process, and the hazardous waste generated in the furnace.

Aspects such as the sizing of the technology must also be taken into account, determining, among other things, the optimum of treated quantities, energy balances, and transport distances.

12.10 Policy Instruments for Pyrolysis in Hungary

12.10.1 Circular Economy in Hungary

The aspect of "circular economy" was entered in European politics in 2015 with an explosion. Its idea was to create a holistic approach in the EU developments. The system solution idea can provide development possibilities across many sectors, by exchanging the traditional "goods from material" linear economic solutions for circles, which was basically a theoretical solution based on lost material cycle production systems (European Commission 2015).

The popularity of the circular approach, and the strong belief in it were dissimilar to other political aspects in the European Union, that is why it deserved a special role. Strictly speaking, the circular economic solution is a system, which substitutes for the linear "end-of-life" abstraction by providing the option of recuperation, promoting the usage of renewable fuel and energy resources, and targets to eliminate waste as a phenomenon by changing the conventional business models (Fogarassy et al. 2016).

To realize these goals On 29 November 2018, the Circular Economy Platform was officially established in Hungary as an initiative of the Business Council for Sustainable Development in Hungary (BCSDH), the Embassy of the Kingdom of the Netherlands, and the Ministry for Innovation and Technology.

The establishment of the Circular Economy Platform was attended by 33 leaders of committed companies, institutions, and organizations, who personally signed the related Memorandum of Understanding. Balázs Weingartner, former minister of state for sustainability, praised the initiative, signing the document on behalf of the Ministry for Innovation and Technology (European Commission, "Circular Economy - Virtuous Circle Tour in Hungary", 2019).

The Business Council declared that the change to a circular economy represents a great business opportunity. While the core of the concept is not yet deeply recognized by most companies, the use of the model can increase the resilience of the world economy and facilitate achievement of the Paris Agreement on climate change and the United Nations Sustainable Development Goals. The circular economy represents a business opportunity worth USD 4.5 trillion by 2030, as the council noted (European Commission 2015).

There is a great need to achieve a circular economy, as the population and thus the demand for raw materials increase, and resources are scarce. In addition, the production, transport, and use of raw materials have a significant impact on the environment. Not incidentally, more efficient use of raw materials could also reduce CO_2 emissions. Waste reduction, eco-design, and re-use could save European businesses a gross € 600 billion and reduce greenhouse gas emissions by 2–4% (European Commission 2018).

In addition, a circular economy would reduce environmental pressure, provide resources for raw materials and improve the EU's competitiveness.

12.10.2 Relevant Regulations and Rules

First of all, I must point out that I will not go into the technical details of the licensing of the plant, the details of emissions and capacity. The reason for this is that this chapter alone would merit a separate, independent article.

For the legal definitions and rules of waste management of waste, we can find two relevancies. One is the Environmental Protection Act of 1995 (Act LIII 1995, called "KTV") and the other is the Waste Management Act (Act XLIII 2000, five years later, called "Hgt"). Due to its earlier entry into force and its more general nature, the "KTV" provided only the most basic framework for classifying certain things as "waste," when it stated:

> Section 30 (1) The protection against the effects of waste on the environment shall extend to all materials and products, including their packaging and wrapping materials, which the owner is unable or unwilling to use in accordance with his original purpose or which arises during their use.

From this, the concept of waste according to the Act can be easily created: all materials and products, including their packaging and wrapping materials, which the owner cannot or does not intend to use in accordance with their original purpose or which is generated during their use.

The latest act to be applied of waste management in Hungary is the 2012 CLXXXV Law on Waste (Act CLXXXV 2012). Its aim is the protection of the environment and human health, the reduction of the environmental impacts, the economical management of natural resources, the reduction of the impact of resource usage, improving its efficiency, and the prevention, reduction, and reduction of the harmful effects of waste generation, the re-use of second-hand products, the maintenance of materials in the consumption chain in the production-consumption cycle, the recovery of waste in as much material as possible and environmentally friendly disposal of non-recoverable, non-recyclable waste. However, it does not cover:

- sewage,
- waste resulting from the exploration, extraction, processing, and storage of mineral resources,

- animal by-products, including processed products derived therefrom, unless they are destined for landfill, incineration or recovery in a biogas or composting plant.

In our case the “incineration” plays a key role, even if we are not technically talking about thermal decomposition.

12.10.3 Applications of Regulations in Practice

In the following chapter, let us have a short examination on the Commission’s legislative package on authorization process of a Pyrolysis Facility. First of all, it should be noted that in 2002, according to the legal background in Hungary, the various thermal recovery processes are considered as incineration according to Hungarian regulations (Szuhi 2013). Accordingly, conforming to point 2 (d) of Decree 3/2002 of the Ministry of the Environment on the incineration of waste: “Waste incineration plant (incineration plant) means any technical installation and associated equipment, whether fixed or mobile, which is designed or used for the incineration of waste or waste gases and whether or not the heat generated during incineration is recovered. This includes incineration of waste by oxidation and other thermal treatment processes such as pyrolysis, gasification or plasma processes, provided that the materials generated during the treatment are subsequently incinerated.”

It can be seen that the condition of “incineration” after the process is not specified. The result of thermal recovery is typically an energy product (oil, gas, coal) that is actually burned (or incinerated as, for example, as a local energy source) in terms of its use.

This logic has led to the misconception that thermal recovery processes, including pyrolysis, gasification, and plasma technologies, are considered as “incineration.” The grouping by incineration has resulted in thermal recovery processes being attacked from many, mainly environmental sides.

Currently, in accordance with Waste Act CLXXXV (2012) the definitions according to the provisions of Act No. 43/2016 Coll. are applicable in the case of recovery operations, which list is in the (VI. 28.) of the Ministry of Finance about disposal and recovery operations related to waste management. This list contains the code “R3” for thermal recovery, as follows: “Recovery, recycling of organic substances not used as solvents, including composting, other biological transformation operations, as well as gasification and pyrolysis, if the components are used as chemicals in the latter up (Act CLXXXV 2012 on Waste).

It can be seen, therefore, that the production of the resulting energy products (oil, gas, coal) counts as recovery operations if the resulting product, if used as a raw material for other production processes.

12.10.4 Conditions for Termination of Waste Status

According to the Waste Act, the elimination of waste status exists if it manufactured material:

- it is used for their intended purpose and in a general manner,
- there is a market or demand for it, it complies with the technical requirements for its intended use and the applicable legislation regulations, standards, and
- its use does not, on the whole, have an adverse effect on the environment or to human health.

Practical examples of waste recovery for the better understanding:

- breaking and classifying construction and demolition waste, and after construction after construction sale as a raw material;
- grinding and granulation of plastic waste;
- car dismantling (sale of dismantled car parts);
- production of alternative fuels from combustible waste (RDF);
- metal casting, etc.

12.10.5 Conformity Assessment

In order to support the above, the waste must be subjected to a conformity assessment or qualification procedure appropriate to the intended recovery purpose. Considering the conformity assessment so far, two Hungarian organizations have applied for the issuance of the certificate, According to regulations the "verification of compliance can be carried out by a statutory certification body," which causes a problem because of the followings:

- The material used in Pyrolysis Facilities usually is tires and plastic, in case of plastic, it is "non-packaging" mixed plastic, which is not covered by the current EC directives (there is a regulation on scrap cars, e-waste, batteries, packaging waste).
- The Pyrolysis Facilities produce different end-products called, e.g., "pyrolysis/thermolysis oil," "pyrolysis/thermolysis gas," and "carbon black/biochar" by using plastics from waste material, industrial scrap, secondary raw material. The quality parameters of the end-products are not defined.
- In case of purchasing the incoming material: usually the incoming plastics are pre-segregated waste-streams originated from settlement management facilities, waste sorting facilities, etc. The reason for this is that all the metal, the debris, the inorganic material must be removed from the stream before entering the pyrolysis technology. The incoming material is not simply "waste" but a prepared secondary raw material, having a certain value.

- Currently, there is no Hungarian government decree on the basis of which an organization certifying compliance could do so, in the absence of a government decree.
- Currently there is no applicable regulation, the "elimination of the waste status of energy-efficient waste and the rules for the use of alternative fuels" is currently only a draft—but if this thermal treatment method is preferred, it must defined precisely.
- Currently, there is no Hungarian certification body that could be technologically prepared for pyrolysis: they does not have a technical background, the output material cannot be interpreted either technological or technical descriptions are expected to be provided from a pyrolysis facility, on the basis of which a certificate on the termination of the waste status of the materials would be issued. Moreover their information states that the current R&D activity does not require a certificate of "end of waste status."
- The generated oil as end-product eliminated to be "waste" if it is or can be used for its intended purpose and in a general manner, there is market or it is in demand.

12.10.6 Certification of Elimination of Waste Status

A quality assurance system suitable for certifying the elimination of waste status must be set-up, which means the following problems:

- In the case of products with variable composition, the set-up of the quality assurance system is diverse, depending on the materials entering the process, their proportion and the expected composition of the output materials.
- Developing a quality assurance system is a complex task by developing a separate sub-system for each process.

In addition, according to the Waste Management Act (Act CLXXXV 2012 on Waste):

- A substance or object that has undergone a recovery operation shall no longer be considered waste if the following conditions are met together:
- used for their intended purpose and in a general manner,
- has a market or demand for it,
- meets the technical requirements for its intended use and the relevant legal requirements, standards, and
- its use does not, on the whole, have an adverse effect on the environment or human health.

A substance or object which ceases to be waste when the conditions set out in the paragraph 1. of the Act (Act CLXXXV 2012 on Waste) are fulfilled shall be considered as recovered, and

- in the Government Decree on Packaging and Packaging Waste Management Activities,
- in the Government Decree on end-of-life vehicles,
- in the Government Decree on Waste Management Activities for Waste Batteries and Accumulators,
- in the Government Decree on Waste Management Activities for Electrical and Electronic Equipment, and
- it ceases to be waste for the purposes of transposition of other relevant Union legislation or for the purposes of recovery and recycling set out in other national legislation, when the recycling or recovery requirements set out in that legislation are met.

It can therefore be stated that the organic material (sludge) used in the course of the activities performed under the pyrolytic conversion does not belong to any of the government decrees on waste management activities related to waste streams.

Pursuant to Section 10 (1) of the Act (Act CLXXXV 2012 on Waste), the specific and detailed requirements necessary for the fulfillment of the conditions for the elimination of waste status, including limit values for pollutants and rules for avoiding possible adverse environmental effects of a substance or object, are laid down in European Parliament Directive 2008/98/EC. and a Union act implementing Article 6 (1) of Council Directive, with the exception set out in paragraph. If no European Union act provides for the conditions for the elimination of waste status for a specific waste stream, the additional conditions for the elimination of waste status and the detailed requirements necessary to meet such conditions shall be laid down in a local government decree (Act CLXXXV 2012 on Waste).

To our knowledge, there is no such legal act, nor is there a Hungarian government decree regulating the detailed requirements necessary to meet the conditions.

Verification of compliance with the conditions for the elimination of waste status may be performed by a certification body specified by law. To the best of my knowledge, such legislation does not exist, there is no legislation on what kind of organization is the “specified certification body,” as I am not considering or manage waste streams under Section 9 (2) of the Waste management Law (Act CLXXXV 2012 on Waste).

As I mentioned above the quality assurance system suitable for certifying the termination of the waste status shall be inspected quarterly by the authorized certification body. The compliance of a substance or object produced by a recovery operation with the conditions for elimination of waste shall be verified by the authority responsible for verifying the conformity and safety of the product and the authority responsible for market surveillance.

To my knowledge, there is neither such authority nor relevant verification system.

The demonstration of the elimination of waste status brings up questions as the followings:

- How can we apply this Act in practice considering the Circular Economy?
- How can we apply this when every material can be used as an input for a certain process (e.g., oil for chemical processes)?
- How can we apply a regulation, when there is no waste, there is no quality assurance system?

Considering the regulations of Solid waste management in Hungary the pyrolysis technology of sewage must consider the following criteria:

- the Thermocatalytic conversion applies modified pyrolysis with the application of catalysts, not incineration;
- the products of thermal recovery are not (biochar) energy product, or they are (oil, gas) but not incinerated;
- the pyrolysis of sewage sludge can be modified to minimize the production of oil (e.g., liqiud products as energy product);
- the gas is used also locally for inertization or "inerting system" instead of other inert gases (e.g., nitrogen) that is actually burned or incinerated as for example a local energy source, in terms of its use.

Conditions for termination of waste status in case of application of pyrolysis of sewage sludge pyrolysis technology:

- the process produces special different end-products called "oil," "gas," and "biochar";
- the "oil" as energy product is considered a household fuel oil by the Authorities (but it is not incinerated);
- a household fuel oil can be measured in accordance to the relevant quality system;
- biochar is used for their intended purpose and in a general manner (e.g., soil conditioner);
- the products are valuable, they can be sold, therefore there is a market or demand for them;
- it complies with the technical requirements for its intended use and the applicable legislation regulations, standards, which is not "incineration";
- on the whole, not have an adverse effect on the environment or to human health.

However, if there is no such EU legal act or legislation, the waste management authority decides on the detailed regulations necessary to fulfill such conditions, which determines the following content elements during the decision (Act CLXXXV 2012 on Waste):

- raw material consisting of permitted waste during the utilization operation;
- authorized treatment procedures and techniques;
- quality criteria for end-of-waste status resulting from a recovery operation in accordance with applicable product standards, including limit values for pollutants where necessary;

- requirements for management systems demonstrating compliance with end-of-waste criteria, including quality control and self-monitoring and, where necessary, accreditation;
- and the requirement for a declaration of conformity.

12.11 Materials and Methods

12.11.1 The Sewage Sludge Samples

The domestic sewage sludge comes from a modern, four-stage municipal (mechanical-biological) sewage treatment plant, which is located in the settlement of Szabadka (Serbia). Sewage sludge was produced using an activated sludge treatment process, followed by drying bed dewatering. Added to this is the sludge from the sewage treatment plant in the settlement of Magyarkanizsa (Serbia), which uses the same technology on a smaller scale, using a press belt dewatering unit for drying.

As the starting material, I used anaerobic sewage sludge fed with municipal water in the sewage treatment plant of Szabadka and Magyarkanizsa, mixed, without determining the ratio of the mixture. The reason for this is that the Serbian research and development project of Research and Development Investor and Operator Ltd. plans to receive the mixed sewage sludge from the above-mentioned two settlements as a plant input, and the process does not differentiate between the sources of the incoming materials. The sewage sludge samples were randomly collected before the transport (the goal is deposition at the Subotica Regional Landfill) in the spring of 2023, and then homogenized into the composite sample.

Dehydrating of stabilized (digested) sludge in sewage treatment plants—the dry matter content of the stabilized sludge leaving the digesters is around 3.5%, to which a polyelectrolyte solution is mixed, and thus water is extracted from it on a belt filter press, until its dry matter content reaches 20–25%. At our request, the sewage treatment plants can provide the sludge produced with any desired moisture content.

The average dry matter content of the mixed sludge is 22.5% based on the measurements made in the sewage treatment plant, which can be considered quite low. Since the planned technology accepts material with a moisture content of less than 25%, which it dries to approximately 15% (air-dry state, between 12 and 16%) in its own stem burner, we adapted the experiments accordingly.

The pyrolytic equipment designed in the planned Serbian research and development project of Openware-SBS Research and Development Investment and Operator Ltd., which later in case of a successful development serves as a case study, is not suitable for ensuring temperatures above 650 °C in terms of operational performance, but the planned maximum heating intensity of 50 °C/min can be ensured for 10 tons per day with capacity.

The mixed sewage sludge was (pre)dried overnight at 110 °C in an air-stirring laboratory oven (approx. 15 wt. % moisture and 32.7 wt. % ash content) to prepare the samples for pyrolysis.

Table 12.6 The names of the samples used based on the pyrolysis temperature and the intensity of heating

Sample name	SZI-0	SZI-1	SZI-2	SZI-3	SZI-4	SZI-5	SZI-6
Pyrolysis temperature	0	300	300	450	450	650	650
Intensity of heating (°C min^{-1})	0	5	50	5	50	5	50

Table 12.7 Heavy metal content of the dried sewage sludge sample

Heavy metal	Cr	Zn	Ni	Cu	Pb	Hg	Cd	Fe
Heavy metal content (ppm)	36	1503	19	227	84	0.8	0.5	7792

Table 12.8 Chemical properties of the control sewage sludge (SZI-0) and the pyrolyzed samples (SZI-1-6)

Sample	SZI-0	SZI-1	SZI-2	SZI-3	SZI-4	SZI-5	SZI-6
Moisture content (m%)	15.1	0.8	0.8	0.6	0.7	1.1	1.1
Ash content (m%)	32.7	54.4	55.8	64.1	66.8	68.2	72.3
Volatile matter content (m%)	55.2	22.4	22.1	18.6	14.9	12.3	10.4
C (m%)	35.4	36.2	28.7	30.5	30.2	32.1	30.6
H (m%)	5.9	3.1	2.4	1.8	1.7	1.1	1.1
N (m%)	3.8	3.7	3.3	3.1	2.9	2.1	1.6
O (m%)	29.3	7.1	6.8	5.3	4.6	1.2	1.1
S (m%)	0.8	0.5	0.5	0.5	0.5	0.5	0.5
C/H	0.6	1.25	1.51	2.7	3.0	4.7	4.9
C/O	1.62	6.8	7.2	10.1	13.6	27.8	30.4

The resulting dry material was ground from its original size (irregular grains with the diameter of 0.5 cm) to a size smaller than 3 mm (1–3 mm fraction). I planned to test the samples at different pyrolysis temperatures (300, 450, and 650 °C) and with heating intensity (two heating rates, 5 and 50 °C/min), therefore they were named accordingly (Table 12.6).

The pyrolysis temperature of the samples planned during the tests was accordingly planned for a maximum of 650 °C.

The basic Waste water sample fractions were chemically analyzed by the Subotica Waste water Treatment Plant (Subotica, Serbia). Table 12.7 summarizes the heavy metal content of the Waste water sample, and the Table 12.8 contains its chemical characteristics. The reason for the involvement of the Subotica Waste water Treatment Plant is that they are obliged to carry out analytical measurements of waste water and sewage sludge, which they regularly perform (Fig. 12.4).

REZULTATI FIZIČKO-HEMIJSKIH LABORATORIJSKIH ISPI IVANJA			
Parametar	Vrednost	MDK [*]	Standard/Metod
Fizičke i fizičko- hemijske karakteristike			
pH vrednost	7.4		ISO 10523:199
Amonijak NH_3 [mg/l]	<0.05		ISO 14911:199
Nitriti NO_2^- [mg/l]	0.075		EPA 300.1
Itrati NO_3^- [mg/l]	1.9		EPA 30
loridi Cl^- [mg/l]	83.3		EPA 300.1
Sulfati SO_4^{-2} [mg/l]	110.6		EPA 300.1
Utrošak $KMnO_4$ [mg/l]	29.4		PRI [2] P-IV-9a
Hemijska potrošnja kiseonika (iz KMnO4) O_2 [mg/l]	7.4		PRI [2] P-IV-9a
Biohemijska potrošnja kiseonika BPK_5,nerazblažen [mg/l]	3.4		SRPS EN 1899-2:09
Elektrolitička provodljivost na 20°C [μS/cm]	1100		SRPS ISO 27888:200
Hemijska potrošnja kiseonika (iz K2Cr2O7) O_2 [mg/l]	32		VDM 0181 [8]
Suspendovane materije na 103-105° C [mg/l]	11		SMEWW 19th [1] m 2540 D.
Sedimentne materije po Inhoff-u posle 2h [ml/l]	0.2		SMEWW 19th m 2540 F.
Fosfor P [mg/l]	0.181		EPA 200.7Rev 5
Fosfati PO4 [mg/l]	0.55		EPA 200.7Rev 5
Smeša organskih jedinjenja			
Deterženti anjonski [mg/l]	<0.1		SMEWW 16th [3] m 512 B.
Metali, tehnika ICP-OES			
Olovo Pb [mg/l]	<0.005		EPA 200.7Rev 5
Kadmijum Cd [mg/l]	<0.0008		EPA 200.7Rev 5
Cink Zn [mg/l]	0.029		EPA 200.7Rev 5
Bakar Cu [mg/l]	0.006		EPA 200.7Rev 5
Nikl Ni [mg/l]	<0.001		EPA 200.7Rev 5
Gvožđe Fe [mg/l]	0.062		EPA 200.7Rev 5
Hrom Cr [mg/l]	<0.001		EPA 200.7Rev 5
Aluminijum Al [mg/l]	<0.003		EPA 200.7Rev 5
Barijum Ba [mg/l]	0.031		EPA 200.7Rev 5
Berilijum Be [mg/l]	<0.0002		EPA 200.7Rev 5
Vanadijum V [mg/l]	<0.001		EPA 200.7Rev 5
Arsen As [mg/l]	<0.02		EPA 200.7Rev 5
Metali spektrofotometrijski			
Hrom Cr^{+6} [mg/l]	<0.05		S EW / 19th m 3500Cr+

Fig. 12.4 Analytical measurement report of the Subotica waste water treatment plant (Subotica, Serbia, sample)

12.11.2 Pyrolysis of Sludge-Like Waste

The pyrolytic transformation of domestic sewage sludge into biochar is a promising method for reducing the residual, large amount of sewage sludge, recycling its high-value heating gas as renewable energy, and using it as soil fertilizer.

Although the effect of pyrolysis temperature on energy recovery has been extensively studied, little information has been found on nutrient recovery and potentially toxic heavy metal content of biochar before it is reused as a soil amendment. The purpose of this chapter is to examine the ideal pyrolysis

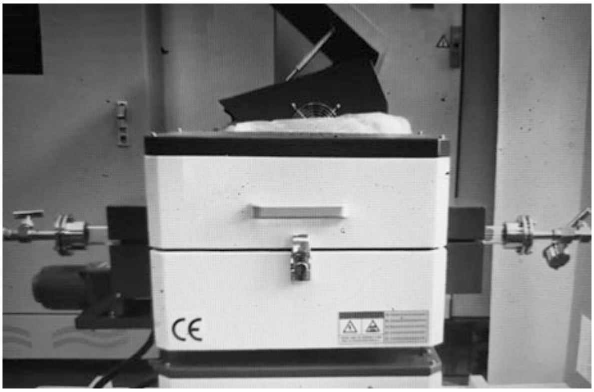

Fig. 12.5 The tube furnace used during the research

temperature, which guarantees a higher yield level on the one hand, and meets the quality standards for soil placement on the other.

I will present this kind of utilization of sewage sludge through the Serbian research and development project of Openware-SBS Research and Development Investment and Operator Ltd. As the starting material for the pyrolysis experiments, I used the prepared sewage sludge from the Waste water treatment plants in Szabadka and Magyarkanizsa, which was pyrolyzed in a laboratory-sized STG-4014 furnace. I changed the pyrolysis conditions, such as the heating rate and the final pyrolysis temperature (between 300 °C and 550 °C) in order to study their effect on the quantitative characteristics of the resulting gases, liquids and solid residues.

The pyrolysis of sewage sludge was carried out in a laboratory horizontal quartz tube furnace (tube reactor, Fig. 12.5) with one zone electric furnace heating. To carry out these pyrolysis experiments, approx. I used 20 g of the 1–3 mm particle size fraction in each run. Different applied pyrolysis temperatures (300, 450, and 650 °C) and heating rates (5 and 50 °C/min) were investigated. Technicality, the equipment is also suitable for pyrolysis at a higher temperature (up to 1400 °C, with a constant output of 1300 °C) with the possibilities for further test with higher temperatures. The names of the samples are accordingly included in Table 12.6 (where SZI means "Szennyvíz Iszap" from Hungarian language).

In the experiments sewage sludge pyrolysis in a tube furnace (Fig. 12.5) was evaluated, where 100 ml/min of N was flowed through the reactor for each pyrolysis process in order to maintain an inert (anoxic) environment. Sewage sludge was pyrolyzed at 300 °C (SZI-2), 450 °C (SZI-4), and 650 °C (SZI-6) for 40 min at a higher heating rate of 50 °C/min. Raw sewage sludge was used as a control and each treatment was performed in duplicate.

After the process of pyrolysis, the sewage sludge samples (raw sludge and biochar) were cooled back to room temperature and stored in an airtight container before analysis. The solid products produced during pyrolysis were subjected to quantitative analysis. I collected the condensable liquid fractions and gave them an analogous name corresponding to the samples. The chemical analysis of the liquid fraction is in progress, but its part is not part of the present thesis.

Gases were added at intervals such that the temperature increased by 10 °C, regardless of the heating rate used in the pyrolysis experiment. After that, the gas samples were collected at the following intervals: 300–350 °C, 450–500 °C, 650–600 °C. Finally, after the pyrolysis was finished, the solid carbonaceous residue was recovered from inside the quartz reactor for further analysis.

12.11.3 Physical and Chemical Characterization of the Raw Sewage Sludge and the Produced Biochar

The chemical characterization of the solid fraction (the biochar) was carried out in external Waste water treatment laboratory as follows: proximate analysis, elemental analysis (a LECO device was used to determine the C, H, and N content and the S content). The structural characterization of the biochar was carried out by physical adsorption of N_2 and CO_2 using the t-plot method (Table 12.9).

The pH and electrical conductivity (EC) were determined in sample water extracts at a ratio of 1:5 and 1:2.5, respectively. The volatile organic matter (VOM) was calculated based on the air-dried mass according to the following equation: VOM(%) $=100 - \text{MC}$ (where MC is the determined mineral content).

The samples pre-dried in the electrical drying oven were weighed first, it was followed by the weight determination of the pyrolyzed samples. The final weight was measured using the same calibrated analytical balance. MC was determined by using the equation: MC (%) $= (m2/m1) \times 100$ (where "$m1$" is the mass of the air-dried, and "$m2$" are the and pyrolyzed sample). Total nitrogen (TN) was determined using the Kjeldahl method (The Kjeldahl nitrogen refers to the sum of ammonia-nitrogen and organic nitrogen. The basis of the method is the conversion of the amino nitrogen of many organic substances into ammonium with the help of sulfuric acid, potassium sulphate and copper-sulphate catalysts). The amount of available phosphorus "orthophosphate" (P) was determined using a colorimetric

Table 12.9 Changes in the physicochemical properties of sewage sludge and biochar samples obtained at different pyrolysis temperatures (300 °C, 450 °C, and 650 °C)

Parameters	SZI0	SZI-2	SZI-4	SZI-6
pH	6.54	6.22	7.74	9.38
EC (mS cm^{-1})	3.22	4.61	4.58	4.66
MC (%)	64.3	68.2	86.4	88.3
VOM (%)	38.7	31.4	17.9	14.3
TOC (%)	23.57	18.71	12.82	8.41
TN (%)	0.027	0.023	0.019	0.011
C/N	605.4	894.34	743.21	168.72
P (mg kg^{-1})	0.011	0.01	0.01	0.01
K (mg kg^{-1})	25.43	41.22	51.47	52.31
Na (mg kg^{-1})	35.85	43.29	52.97	51.93

method. Bases (Na^+ and K^+) exchangeable with HCl (6N) were extracted from the generated biochar and measured by atomic adsorption.

The most important factor for the experiment, the heavy metals (Cu, Cd, Zn, Pb, and Cr) were determined by mixing 0.5 g of samples with 5 ml of hydrochloric acid and HNO_3. After acid digestion, the mixtures were filtered and measured by Atomic Absorption Spectrometry (AAS).

12.12 Results and Discussion

12.12.1 The Resulting Pyrolysis Products

It can be stated that the quantity, yield, and composition of the pyrolysis products obtained from sewage sludge depend on the operating conditions of the technology, where mainly the physical parameters play a role. Figure 12.6 provides information about the evolution of the gas, liquid, and solid fraction yield with pyrolysis temperature and heating intensity (Inguanzo et al. 2002). As reported by other authors who work with similar and even different types of waste (e.g., sewage sludge, animal manure, but also municipal waste and plastics (Basu 2010)). The increase in the final temperature of pyrolysis causes a decrease in the solid fraction and an increase in the gas fraction. The liquid fraction increases slightly when the final temperature is increased from 450 °C to 650 °C, but remains more or less constant above 650 °C.

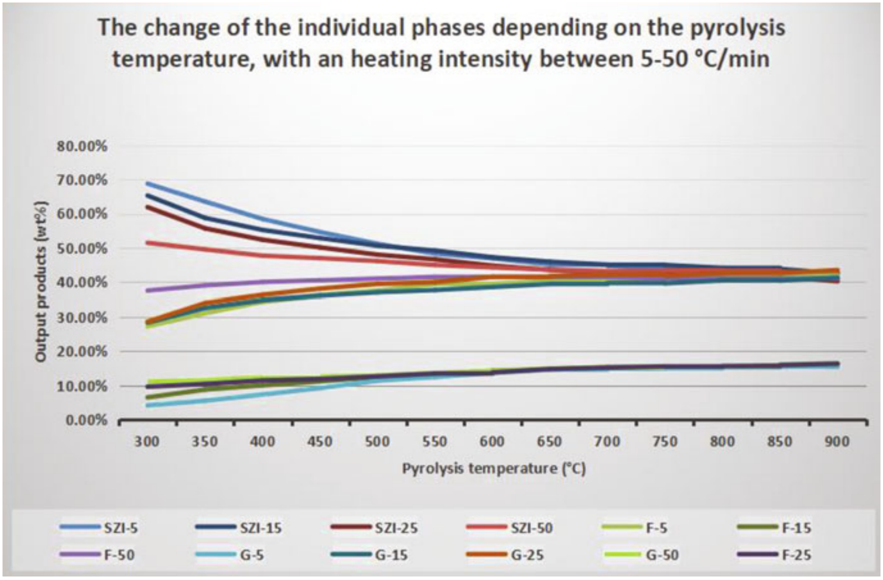

Fig. 12.6 Change in the yield of solid, liquid, and gas products depending on the pyrolysis conditions (different heating intensity, temperature)

The effect of the heating rate is only important at a low final temperature (i.e., 450 °C in our case). Thus, at this temperature, the more intense the heating rate, the more efficient the pyrolysis, which results in greater liquid and gas production and a reduction in the amount of solid residue. This phenomenon is minimal at temperatures higher than 650 °C, the effect is practically negligible (Inguanzo et al. 2002).

The yield and composition of resulting pyrolysis products obtained from sewage sludge is not only a question of the quality parameters of the products created. The quantitative parameters of each product must be taken into account, from an economic and circularity point of view. Given that the generated energy products can be used locally, the technology basically defines the technology to meet the energy requirements of the operating conditions. The use of locally generated energy products in the technology reduces the intake of external, typically fossil, energy carriers, which reduces the environmental footprint of the technology and implements Circular Economy in practice.

12.12.2 The Solid Fraction: Biochar

Some chemical properties of the solid residues of the pyrolysis are summarized in Table 12.8. During the pyrolysis of sewage sludge, a significant ash content of 54–55 m% and a high carbon content is produced if the pyrolysis is carried out at 450 °C, this value changes to 64–66 m% at 650 °C. However, pyrolysis does not appear to be complete even at 650 °C, and some volatile matter remains in the carbonaceous materials (10.4 m% at 650 °C). However, at high temperatures (650–850 °C), the volatilization slows down, showing a similar trend to the carbonization of coal and biomass.

This, and the fact that the energy investment (heating intensity) between 450 °C and 650 °C does not yield a significant solid product output, we consider this temperature range to be operational, and we take it under further investigation when testing heavy metals.

In principle, several methods can be used to dispose of the carbonaceous residues produced during the pyrolysis of sewage sludge:

- can be burned alone or mixed with other fuels (co-combustion);
- can be disposed of by landfill;
- can be used as adsorbents for suitable pollutants (reuse), even before applying one of the two previous options;
- with the provision of appropriate chemical parameters, it can be applied to agricultural fields as “biochar,” considering the relevant rules.

The energetic use of biochar is determined by the calorific value of pyrolyzed residues (Table 12.10), which slightly decreases with increasing pyrolysis temperature and heating rate. However, these values are quite similar, regardless of the pyrolysis conditions used, and are relatively low compared to other fuels

Table 12.10 Calorific value of pyrolyzed solid residues of sewage sludge (Inguanzo et al. 2002)

Material	Heating value
Coal	14,600–267,900 (kJ/kg)
Plastics, wood, paper, rags, garbage	17,600–20,000 (kJ/kg)
Wood	16,000–20,000 (kJ/kg)
Dry sewage sludge	12,000–20,000 (kJ/kg)
Wet sewage sludge	1000–3000 (kJ/kg)
Gas-oil	45,500 (kJ /kg)
Black liquor	12,500–15,500 (kJ/kg)
Natural gas	3800 (kJ/m^3)
Coke-oven gas	19,000–22,000 (kJ/m^3)
Synthetic coal gas	10,800 (kJ/m^3)
Blast-furnace gas	4400—5300 (kJ/m^3)

Table 12.11 Main structural properties of sludge (SZI-0) and pyrolytic carbonaceous solids (biochar samples, SZI-0–SZI-6)

	Biochar samples						
	SZI-0	SZI-1	SZI-2	SZI-3	SZI-4	SZI-5	SZI-6
True density (He, g/cm^{-3})	1.65	1.86	1.97	2.03	2.15	23.4	23.5
Porosity (%)	42	36.7	39.4	41.8	48.4	51.6	54.3
Macropore volume (mm^3/g)	–	325	395	410	372	365	384
Mesopore volume (mm^3/g)	–	9	12	13	16	13	21
Micropore volume (mm^3/g)	–	22	10	46	48	46	81

(Table 12.11), or to the value of dry sewage sludge itself. The possibility of incineration (or co-incineration) cannot be completely ruled out, but in the case of a relatively low calorific value and a high concentration of heavy metals, it is not a problem-free solution. It should also be borne in mind that the heavy metals remaining in the pyrolyzed residues are more resistant to natural leaching than the heavy metals in the ash produced during combustion or in the raw sludge itself (Inguanzo et al. 2002).

The advantage is that pyrolysis offers the possibility of a large weight reduction. When disposing of it by landfilling, it is important to consider the reduction of the amount of raw sewage sludge available through pyrolysis. This can be calculated from the solids amounts and density (Table 12.11). Figure 12.9 shows the development of weight reduction under pyrolysis conditions.

The weight loss increases with the pyrolysis temperature, but mainly with the heating rate. Thus, compared to dry sewage sludge, a 40–50% weight reduction can be achieved for samples above 650 °C. It can be seen that if the reduction were to be compared to the volume of wet sewage sludge, it would be significantly greater due to its higher water content (Fig. 12.7).

The third option, which uses carbonaceous residues of pyrolysis as an adsorbent for pollution control, is compatible with—and technically precedes—the two previous options. Carbonaceous residues can first be used as absorbents and then incinerated or landfilled.

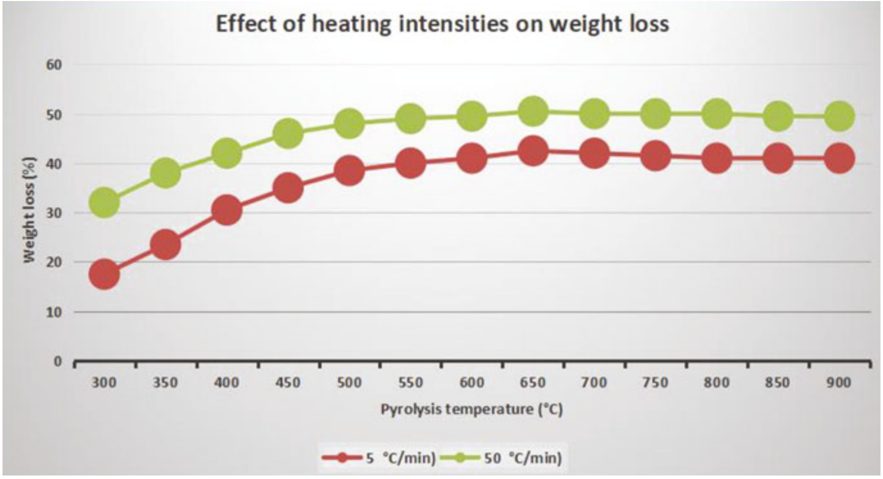

Fig. 12.7 Reduction of sewage sludge weight at different pyrolysis temperatures and heating intensities (5 and 50 °C/min)

From a structural point of view, the porosity of the generated "biochar" is 36–54% (Inguanzo et al. 2002). However, most of this porosity is due to macropores, the volume of meso- and micropores being relatively low (Table 12.8) compared to other typical adsorbents (Table 12.11).

The textural characteristics of the remaining biochar can in principle make them suitable as "cheap" adsorbents for large molecules produced in Waste water treatment processes. However, further studies are needed to determine whether this is possible with the carbonaceous residues present or whether additional activation is required (if possible).

The fourth option is to apply it to the field as "biochar" with the appropriate parameters (improves nutrient and physical soil quality), which, as the main technological goal, receives a separate chapter due to its importance.

12.12.3 The Liquid Fraction

The planed Serbian project of Openware-SBS Research and Development Investment and Operator Ltd. did not perform any measurements related to the analysis of the composition of the used sewage sludge pyrolysis liquid products. In this matter, until the measurements are carried out, we have to rely on the literature.

The condensing vapors represent the liquid fraction of the pyrolysis products. This fraction can be divided into an aqueous fraction, which contains water and water-soluble organic compounds (due to the water content of sewage sludge), and an organic fraction, which contains other substances.

If the sewage sludge is dried to a constant mass (air-dry), then the water fraction is minimal (zero), but such a state cannot be achieved on an industrial scale. The technology of pre-drying is not suitable for this, nor is it technologically possible to dry and preserve a larger amount (5–10 tons) of sewage sludge in an air-dry state. In real conditions, drying to a moisture content between 15% and 30% can be solved, so we considered this as the target state.

If the aqueous fraction is present, it accounts for 30–40% by weight of the total liquid fraction (Inguanzo et al. 2002). This is important because part of the liquid phase is an oil-like energy product, but the aqueous phase is technologically polluted water—the treatment of which must be dealt with. The aqueous fraction and the organic fraction can be separated from each other, and the technology itself is capable of this.

The importance of the quantitative and qualitative parameters of the organic fraction must be emphasized. In this, the heating value of the organic fraction plays a prominent role, that is, the determination of whether the organic fraction can be used to extract energy, to meet the technology's own energy needs. In order to learn about the organic fractions, a comparative chromatographic analysis of the samples obtained under different pyrolysis conditions is necessary. In the near future, a more exhaustive quantitative characterization of these materials will take place in order to obtain a more accurate picture of the quantitative composition (Basu 2010).

Based on the literature data, some interesting facts can be deduced from the characterization of the liquid fraction (Inguanzo et al. 2002). It can be observed that the yield of the liquid fraction at a low pyrolysis temperature, i.e., in our case at 450 °C, which is considered to be the average valueis higher with a fast heating intensity speed (here: 50 °C min^{-1}) than in the case of a low heating intensity (here: 5° C min^{-1}).

At a given, constant temperature, the pyrolytic reactions are aided by the high heating rate (here: 50 °C min^{-1}), in which case lighter, shorter carbon chain compounds are formed. These can be easily removed from the reactor, resulting in a higher proportion of the liquid organic fraction in the products.

At higher temperatures above 650 °C, no increase in the yield of the liquid fraction is observed, which suggests that all condensable compounds are already released, so that the remaining volatile substances cannot be condensed. In fact, at higher temperatures, the heating rate has almost no effect on the liquid yield (Inguanzo et al. 2002). In contrast, as the pyrolysis temperature and heating rate increase in the range of 450–650 °C, the C/O ratio in the oil fraction decreases, indicating that the number of oxygenated compounds has increased (Inguanzo et al. 2002).

12.12.4 The Gas Faction

The Serbian research and development project of Openware-SBS Research and Development Investment and Operator Ltd. did not carry out any measurements related to the analysis of the composition of the gaseous products of the used sewage sludge pyrolysis. In this matter, until local measurements are carried out, we must also rely on the literature.

According to a literature review of the gas fraction of sewage sludge pyrolysis, CO_2, CO, H_2, O_2, N_2 és C_xH_y are the main components released during the process a folyamat során felszabaduló fő komponensek (Inguanzo et al. 2002). Regarding the literature, the following general comments should be made regarding the two heating rates used:

(a) At lower applied temperatures (250–350 °C), CO_2 is the dominant gas, although N_2 is also present;
(b) Increasing the pyrolysis temperature leads to a decrease in CO_2 and an increase in CO and H_2;
(c) For the hydrocarbons CH_4, C_2H_4, and C_2H_6, the maximum yields are reached at a temperature of around 600 °C for CH_4 and at a temperature of around 450 °C for C_2H_4 and C_2H_6;

The temperature at which the gases reach their maximum does not show any difference when the heating rate changes, the maxima are the same. However, some, mainly quantitative, differences can be observed here as well. Thus, for any pyrolysis temperature, the concentration of all gaseous components increases with increasing heating rate, except for CO_2, C_2H_4, and C_2H_6. These gases are produced in a lower heat intensity than in the case of application of a high one (Inguanzo et al. 2002).

From a technological point of view, the calorific value of the generated gaseous phase is important. On the one hand, it determines the use of gases as an energy product. On the other hand, in addition to on-site use, satisfying the technology's energy needs, it determines its components (gas—or hybrid burners for pyrolysis reactors, the built-in heating capacities, pre-dryers).

The development of the calorific value of the gases released during pyrolysis is clearly influenced by the development of hydrocarbons in the gases, which can be achieved at a temperature of around 455 °C during pyrolysis with a slow increasing of temperature (low intensity). This corresponds to C_2H_4 and C_2H_6. maximum output (Inguanzo et al. 2002). With a rapid rise in temperature as high heating intensity, the release of these gases takes place in a higher temperature range exceeding 600 °C, and CH_4, H_2 and CO are present in higher concentrations. This explains why the maximum heating value appears at a higher temperature at this heating rate.

Another characteristic of pyrolysis gases, which is important from the point of view of use, is that the average heating values are 12,000 and 13,000 kJ/m^3, which, compared to other synthetic coal gases, are higher than those of, e.g., furnace gases (Inguanzo et al. 2002). Furthermore, the present pyrolysis technology optimized for a gas yield results in maximum heating values between 25,000 and 20,000 kJ/m^3 (Rumphorst and Ringel 1994), therefore optimization of the pyrolysis process would likely result in gases with a similar heating value as a coke-oven gas that can be used process for its own energy supply (Inguanzo et al. 2002). In the same method, the gas fraction of the pyrolysis of sewage sludge, which constitutes a significant part of the pyrolysis products, can be burned again in order to increase the energy balance of the process.

Regarding the physical parameters of pyrolysis, it can be stated:

- Increasing its temperature reduces the yield of the solid fraction and increases the yield of the gas fraction, while that of the liquid fraction remains almost constant;
- The effect of the heating rate was important only at low final pyrolysis temperatures;
- Regardless of the pyrolysis conditions, all the obtained solid products (biochar) are basic in nature and highly macroporous, the meso- and micropore volume is relatively low;
- Both the resulting oils and the resulting gases showed a relatively high heating value as a whole, which can be compared with some traditional fuels, which reveals the use of these products as fuel.

12.12.5 The Effects of Temperature of Pyrolysis on Biochar Chemical Properties and Heavy Metals

The samples were pyrolyzed at 300 °C, 450 °C, and 650 °C with a residence time of 40 min. The analysis of the raw sewage sludge and the generated biochar is in accordance with Regulation 36/2006. (V. 18.) Ministry of Agriculture and Rural Development decree on the licensing, storage, distribution, and use of crop-enhancing substances "(Hungarian Ministry of Agriculture and Rural Development Decree No.36/2006 n.d.) was carried out taking into account the values determined by the volatile organic matter (VOM), mineral content (MC), nutrient content (total nitrogen TN, available phosphorus P and potassium K), measuring its alkalinity (pH) salinity (electrical conductivity EC and Na), and the toxic effect of biochar from sewage sludge by analyzing heavy metals (Pb, Cr, Cd, Cu, and Zn) and was evaluated by the Subotica Central Waste water Treatment Specialists, with the use of a laboratory. Table 12.6 were pyrolyzed at 300 °C, 450 °C, and 650 °C with a residence time of 40 min. The analysis of the raw sewage sludge and the generated biochar is in accordance with Regulation 36/2006. (V. 18.) Ministry of Agriculture and Rural Development decree on the licensing, storage, distribution, and use of crop-enhancing substances" (Hungarian Ministry of Agriculture and Rural Development Decree No.36/2006 n.d.) was carried out taking into account the values determined by the volatile organic matter (VOM), mineral content (MC), nutrient content (total nitrogen—TN, available phosphorus—P and potassium—K), measuring its alkalinity (pH) salinity (electrical conductivity EC and Na), and the toxic effect of biochar from sewage sludge by analyzing heavy metals (Pb, Cr, Cd, Cu, and Zn) and was evaluated in external laboratory.

As expected, pyrolysis temperature has a significant effect on biochar characteristics. The higher VOM, TN, and P content of the biochar sample (SZI-0 and SZI-1) produced at low temperature (300 °C) is justified. However, higher pH, EC, Na, and K were found in the biochar samples produced at higher temperatures (450 and 650 °C) (SZI-3, SZI-4, SZI-5, and SZI-6). The effect of the pyrolysis temperature on the concentration of heavy metals showed a different pattern for each element, indicating a lower level of biochar (SZI-4) produced at 450 °C. This highlights that 450 °C is the ideal pyrolysis temperature for the safe reuse of sewage sludge as a soil amendment.

As I explained earlier, decree 36/2006. (V. 18.) of Hungarian Ministry of Agriculture and Rural Development on the licensing, storage, distribution, and use of crop-enhancing substances (Hungarian Ministry of Agriculture and Rural Development Decree No.36/2006 n.d.) defines domestic sewage sludge as a by-product of the sewage treatment process and refers to it as a stable substance (Hungarian Ministry of Agriculture and Rural Development Decree No.36/2006 n.d.). The production of domestic sewage sludge increases with population growth, urbanization (connections), rapid industrialization, and positive changes in consumption. Sewage sludge can be a potential source of valuable resources and energy, as sludge has a high organic matter content and is rich in plant nutrients. When applied to the soil, sewage sludge can improve soil fertility levels and enhance plant growth, especially in arid and semi-arid areas (Tomócsik 2021). It is known that sewage sludge can contain potentially toxic elements, such as salts, heavy metals, organic pollutants, drug and pesticide residues, and other pathogenic organisms. If sewage sludge is not treated properly, it can have a negative impact on human health and the environment. Pyrolysis, which is a thermochemical reaction, is suitable for pretreatment. The process is carried out at elevated temperatures (450–1100 °C) and in an inert (nitrogen application) atmosphere. Depending on the optimized operating conditions, the purpose of pyrolysis can be to extract liquid ("bio-oil"), gas (hydrogen) or solid (biochar). The characteristics of biochar depend to a large extent on the conditions of the pyrolysis process, especially on temperature and the intensity of heating.

Temperature is one of the most important physical parameters of the pyrolysis process, which can significantly affect the chemical and physical properties of biochar, in terms of pore size distribution, functional groups, elemental composition, and pH value (Rahma et al. 2021).

At low temperatures (>300–450 °C), biochar results in a greater recovery of C and other nutrients (this in itself depends on the raw material, so it depends on the sludge), which are usually lost at higher temperatures. A higher pyrolysis temperature results in an increase in surface area, acid fractions, pH, and volatiles.

Residence time is another important factor affecting biochar characteristics and production costs. A short residence time (a few minutes) can lead to incomplete carbonization of the raw material, which reduces the stability of the biochar and the possibility of carbon sequestration. This is the most efficient method of producing biofuels for heat and power generation. A longer residence time (up to a few hours) is essential for the production of biochar. Some heavy metals (e.g., Cd and Zn) evaporate after a residence time of 30 min, and copper, nickel, and phosphorus are immobilized in the biochar after a residence time of 40 min (Rahma et al. 2021).

The pyrolysis of sewage sludge has also been investigated to produce a solid adsorbent (biochar) that can be used for water treatment and the binding of pollutants. Sewage sludge pyrolysis also causes the thermal decomposition of pathogens and some toxic organic compounds, which is necessary for possible application to the soil. Consequently, biochar from sewage sludge can have significant effects on the physical, chemical, and biological properties of depleted soils without posing a contamination risk.

As is known, most studies focused on yield, elemental composition (C, H, O, N), mineral content (ash), pH, specific surface area, and metal content. However, the effect of the pyrolysis temperature on the nutrient status (total C and N, as well as available P and K) and salinity (EC, Na) of the resulting biochar is small (Rahma et al. 2021).

The evaluation of the heavy metal content of biochar is also extremely important from the point of view of the biochar's suitability, even before it is applied to the soil.

12.12.6 The Effect of Pyrolysis Temperature on Plant Nutrients

The increase in the pyrolysis temperature has a significant effect on the change in the physico-chemical properties of sewage sludge. As the pyrolysis temperature increases, the volatile organic matter (VOM) content of the produced biochar decreases from 30.9 (300 °C) to 14.2 (450 °C) and 11% (650 °C) compared to raw sewage sludge (Rahma et al. 2021).

At temperatures below 450 °C, low-molecular-weight polymers are easily degraded, while high-molecular-weight polymers are highly resistant to thermal degradation. Accordingly, low-temperature pyrolysis was waived due to longer carbon chain pesticides, drug residues and especially microplastics remaining in sewage sludge (Rahma et al. 2021). The decrease in the amount of volatile substances reflects the formation of recalcitrant compounds and the increase of stable carbon resistant to CO_2 evaporation. In this regard, biochar-char sequestration takes longer; therefore, its production and land use can help mitigate climate change. In addition, the decomposition of organic matter during pyrolysis creates more pores. In addition, the decomposition of organic matter during pyrolysis creates more pores (Rahma et al. 2021) and increases the surface area of biochar. Modification of such biochars can help retain nutrients and water needed for plant growth.

12.12.7 Nitrogen

A significant decrease can be observed in the case of TN with increasing temperature as follows: digested sewage sludge > SZI-2 (300 °C) > SZI-4 (450 °C) > SZI-6 (650 °C). For example, TN decreases by 48.7, 67.6, and 89.2% after pyrolysis at 300, 450, and 650 °C, respectively. The nitrogen content of biochar decreases as the pyrolysis temperature increases, as the nitrogen element starts to evaporate at low temperatures (about 200 °C) due to the splitting and tearing of weak bonds within the biochar structure. It can be shown that a large amount of N is lost in the form of N_2O, NO, and NO_2 (Rahma et al. 2021).

As the pyrolysis temperature rises above 300 °C, nitrogen is converted to a more stable heterocyclic aromatic form (e.g., pyridine) (Rahma et al. 2021). In this regard, land application of biochar produced at higher temperatures can reduce NH3 volatilization, N2O emissions, and nitrogen leaching (Rahma et al. 2021). The C/N ratio is generally used as a good indicator of the state of nutrients during mineralization. This reflects the ability of organic substrates to release inorganic nitrogen when incorporated into the soil. The change in C/N depends on the amount of total organic carbon (TOC) and total nitrogen (TN).

The level of total nitrogen (TN) is relatively lower in biochars. However, due to their very high TOC content, the C/N ratios are quite high (Table 12.9). The significant decrease of C/N with the increase of pyrolytic temperatures from 300 °C (SZI-2) to 450 °C (SZI-4) and 650 °C (SZI-6) is primarily attributed to the sequestration of organic C, which is VOM loss is reflected (Table 12.9), Accordingly, biochars with higher C/N content (SZI-2 and SZI-4) can be useful as soil amendments, as they promote microbial immobilization and slow down the mineralization rate (Rahma et al. 2021).

12.12.8 Phosphorus

Phosphorus (P) is the second most important nutrient for plant growth after nitrogen. In this study, available P follows the same trend as total nitrogen, showing a minimal but lower concentration in biochar samples produced at 450 and 650 °C (0.01 mg/kg) than for raw sewage sludge (i.e., SZI-0, 0.011 mg/kg). These concentrations are well below the range of desirable available P content recommended for plant growth (0.2 and 50 mg/kg).

Volatilization of phosphorus starts at 700 °C, which suggests that available P in biochar samples produced at high temperatures becomes unavailable. This is consistent with their results reporting a significant decrease in P solubility in biochars compared to sewage sludge feedstock (Rahma et al. 2021). During the pyrolysis process, organic phosphorus is converted to insoluble phosphate (e.g., $CaPO_4$, $FePO_4$, or $MgPO_4$), thus reducing the risk of P loss due to runoff or leaching. The biochar can play an important role in recycling P as mineral phosphorus stocks decrease, from wastes such as domestic sewage sludge (Rahma et al. 2021).

The solubility of P in the soil is primarily regulated by the interaction of phosphorus Ca^{2+}, Mg^{2+}, Al^{3+} és Fe^{2+}/Fe^{3+} with the formation of Ca-Mg-Al or Fe-phosphates. When biochar is applied to acidic soil, the soil pH increases and the amount of adsorbed P decreases and becomes more available. The addition of biochar can significantly increase the availability of phosphorus in agricultural soils by 460% (Rahma et al. 2021).

12.12.9 Effect of Temperature on Mineral Content

The Mineral Content (MC) increases with the pyrolysis temperature, which highlights the highest percentage in the samples produced at 450 °C (SZI-4: 85.5%) and 650 °C (SZI-6: 89%) in biochar (Table 12.9).

The mineral content corresponds to the remaining, non-combustible component, i.e., "ash." Biochars from sewage sludge are characterized by a high ash content (54–72%). Biochars with a high mineral content have a higher CEC. This is attributed to the formation of O-containing surface functional groups, including alkali metals, alkali metals, and polycyclic aromatic hydrocarbons (Rahma et al. 2021). The greater the degree of formation of aromatic structures, the greater the biochar's resistance to microbial degradation. Concentrations of these nonpyrolized inorganic elements can increase biochar pH and affect soil chemistry (e.g., soil pH, nutrient availability, and metal toxicity).

The pH increases proportionally with the pyrolysis temperature, reaching 8.8 (at 450 °C) and 10.5 (at 650 °C) compared to the raw material (6.9) (Table 12.9). The higher pH value of SZI-4 and SZI-6 biochar is the result of the accumulation of alkaline salts (i.e., Na, K, Ca, and Mg). In this study, both Na and K increase simultaneously with increasing pyrolysis temperature. Thus, K increases by 41.22, 51.47, 52.31, and 48.61% for SZI-2, SZI-4, and SZI-6. And Na is 43.29, 52.97, 51.93, which is 69.03% (Table 12.9). Therefore, Na and K show higher concentrations in biochars with the highest pH (SZI-4 and SZI-6) (7.74 and 9.38), which confirms the relationship between alkaline salts and pH.

Above pyrolysis temperature of 300 °C, the alkali metals begin to separate from the organic matrix and increase the pH of the product. The pH stabilizes at a temperature of around 600 °C, while all the alkaline salts are released from the pyrolytic structure.

According to the literature, at around 200–300 °C, cellulose and hemicellulose decompose and produce organic acids and phenolic substances that lower the pH of the products (Rahma et al. 2021). In addition to pH, EC also increases in biochars produced at 450 and 650 °C (SZI-4 and SZI-6), reaching values of 4.58 and 4.66 mS/cm compared to the control (3.22 mS/cm, Table 12.9).

In the case of alkaline soils, the appropriate selection of raw materials and the optimized pyrolysis temperature are important for the production of targeted biochar, which prevents salt accumulation and soil salinization. Field application of biochar should be controlled especially on dry soils characterized by dry periods, which increase the accumulation of salt on the soil surface, leading to secondary soil salinization.

12.12.10 The Effect of Temperature on the Concentration of Heavy Metals

As described in the previous chapters, in addition to the application of the appropriate physical parameters, the reuse of domestic sewage sludge is a reliable and

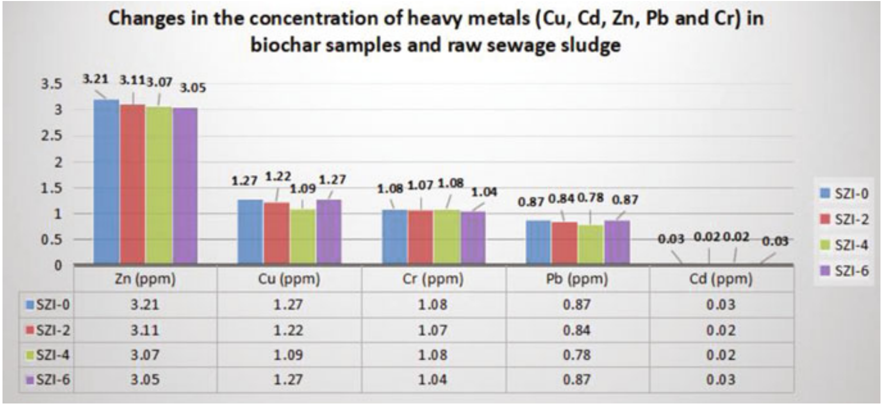

Fig. 12.8 Changes in the concentration of heavy metals in biochar samples produced and sewage sludge (sample SZ-0)

effective method for improving soil fertility, as it increases the organic matter content of the soil, improves the storage of organic matter, and allows plant nutrients (N, P, K) recycling. It is known that sewage sludge can be contaminated with toxic heavy metals and pathogens, as well as microplastics and toxic organic substances such as PAHs and plasticizers. The presence of microplastics should also be mentioned. Therefore, according to EU-conform Hungarian legislative directives they cannot be applied directly without pretreatment in agricultural fields (Rahma et al. 2021).

One of the major characteristics of the pyrolysis process overall is the disinfection of sewage sludge pathogens and the breakdown of organic compounds, as well as the microplastics.

The presence of metals in biochar basically depends on the origin of the raw material or the physical conditions of pyrolysis, which can promote their accumulation in the remaining biochar or their evaporation with the gas fraction. This results that heavy metals (e.g., Zn, Cu, Cr, Pb, and Cd) initially present in raw sewage sludge are concentrated in the generated biochar samples (Fig. 12.8).

As shown in the figure (Fig. 12.8) the heavy metal content of sewage sludge differs significantly in terms of individual elements, creating the following sequence (Rahma et al. 2021):

$$\mathrm{Zn} \rightarrow \mathrm{Cu} \rightarrow \mathrm{Cr} \rightarrow \mathrm{Pb} \rightarrow \mathrm{Cd}$$

Cd content is low, below 0.03 ppm, but Zn exceeds 3 ppm. Zn is the element with the highest concentration. The second is Cu. Cd is the heavy metal with the lowest concentration in the sewage sludge sample and in the biochar produced from it. The Cd content is low because it tends to evaporate during pyrolysis. Other heavy metals initially present in the raw material are usually retained and concentrated in the biochar (Rahma et al. 2021).

Table 12.12 The heavy metal content of biochar produced by pyrolysis in proportion to the original raw material (Rahma et al. 2021)

Zn	Cu	Cr	Pb	Cd
96.4–99.5%	81.5–94.5%	70.0–87.5%	90.4–98.3%	85.8–98.5%

In the biochar samples (samples SZI-2, SZI-4, SZI-6) the concentration of heavy metals (Zn, Cu, Cr, and Cd) does not differ significantly from those in the raw material (sample SZI-0). The total concentration of Zn in SZI-4 and SZI-6 biochar samples decreases significantly with the increase in pyrolysis temperature. On the other hand, the concentration of Cu, Pb, and Cd decreases significantly in biochar (SZI-2 and SZI-4) and increases in SZI-6, without showing significant differences compared to the raw material (SZI-0). Regarding Cr, the concentration decreases significantly in SZI-2 (300 °C) and SZI-6 (650 °C) and increases in SZI-4 (450 °C).

According to the cited literature (Rahma et al. 2021) biochar from sewage sludge pyrolyzed at 500 °C retains 31% of copper, 30% of Pb, and approximately 28% of Cd and Zn compared to the raw material. According to additional literature (Rahma et al. 2021; Rumphorst and Ringel 1994) the biochar produced from pyrolyzed sewage sludge at different temperatures (e.g., on 300, 400, 500, 600, and 700 °C) contains the remaining heavy metals in the ratio of the input in the ratio as it is shown in the Table 12.12.

This phenomenon has also been observed in other studies during the pyrolysis of other raw materials (Rumphorst and Ringel 1994), which attributes the retention of heavy metals to their low volatility.

Overall, the total concentration of the five heavy metals in biochars (Zn, Cr, Pb, Cd in SZI-2, SZI-4, and SZI-6 samples) remains below the regulatory limits defined by the European Biochar Certificate which is extremely important in terms of the application of biochar produced during pyrolysis to fields (Fig. 12.9, Table 12.13).

12.13 Conclusions

It is a well-known fact that the amount of sewage sludge produced worldwide causes serious problems. Its solution cannot wait, because the amount of sewage sludge is constantly increasing. In addition to nitrogen, phosphorus and potassium active substances, municipal sewage sludge also provides micronutrients, and there are many methods for their treatment.

The utilization and disposal of sewage sludge by composting is one of these possible and most widely used solutions. On the other hand, the conversion of domestic sewage sludge into biochar and other energy products by pyrolysis is a promising alternative for reducing the amount of domestic sewage sludge and simultaneously using it as a soil fertilizer. It is widely accepted and well known in the literature that among the physical parameters of pyrolysis, temperature has the most significant effect on the properties of biochar. The purpose of this study is to

EBC - Label EBC - Class		EBC-Feed Class I	EBC-AgroBio Class II	EBC-Agro Class III	EBC-Material Class IV
Elemental analysis	C-total, C_{org}, H, N, O, S, ash				
	H/Corg	< 0,7	< 0,7	< 0,7	< 0,7
	O/Corg	< 0,4	< 0,4	< 0,4	< 0,4
Physical parameters	Water content, dry matter (DM), bulk density (TS), specific surface area (BET), pH, salt content				
TGA	Only once for the first production batch of a pyroylsis unit				
Nutrients	at least N, P, K, Mg, Ca				
Heavy metals	Pb	10 g t^{-1} (88%DM)	45 g t^{-1} DM	150 g t^{-1} DM	250 g t^{-1} DM
	Cd	0.8 g t^{-1} (88% DM)	0.7 g t^{-1} DM	1,5 g t^{-1} DM	5 g t^{-1} DM
	Cu	70 g t^{-1}DM	70 g t^{-1}DM	100 g t^{-1} DM	250 g t^{-1} DM
	Ni	25 g t^{-1} DM	25 g t^{-1} DM	50 g t^{-1} DM	250 g t^{-1} DM
	Hg	0.1 g t^{-1} (88% DM)	0.4 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM
	Zn	200 g t^{-1} DM	200 g t^{-1} DM	400 g t^{-1} DM	750 g t^{-1} DM
	Cr	70 g t^{-1} DM	70 g t^{-1} DM	90 g t^{-1} DM	250 g t^{-1} DM
	As	2 g t^{-1} (88% DM)	13 g t^{-1} DM	13 g t^{-1} DM	15 g t^{-1} DM
Organic contaminents	16 EPA PAH	4±2 g t^{-1} DM	4±2 g t^{-1} DM	6.0+2.2 g t^{-1} DM	30g t^{-1} DM
	Benzo[a] pyren	25 mg t^{-1} (88% DM)			
	PCB, PCDD/F	See chapter 9	Once per pyrolysis unit for the first production batch. For PCB: 0.2 mg kg^{-1} DM, for PCDD/F: 20 ng kg^{-1} (I-TEQ OMS), respectively		

Fig. 12.9 Regulatory limits defined by the European Biochar Certificate (Schmidt et al. 2021)

Table 12.13 Compliance of the total concentration of heavy metals with the regulatory limit values defined by the European Biochar Certificate (Schmidt et al. 2021)

Sample	SZI-0	SZI-2	SZI-4	SZI-6	Limit values according to EBC (2012) European Biochar Certificate (ppm)
Zn (ppm)	3.21	3.11	3.07	3.05	200
Cu (ppm)	1.27	1.22	1.09	1.27	70
Cr (ppm)	1.08	1.07	1.08	1.04	70
Pb (ppm)	0.87	0.84	0.78	0.87	10
Cd (ppm)	0.03	0.02	0.02	0.03	0.8

give a thesis to the question of whether there is a temperature parameter among the physical parameters of pyrolysis that affects the remaining heavy metal content of biochar.

The methodology of the research is to find the physical parameters of the applied pyrolysis, to minimize the heavy metal content of the biochar, instead of focusing on a higher yield of the exiting products. This paper investigates the pyrolysis of sewage sludge at higher temperatures (300, 450, and 650 °C) and compares it with the raw material. The agronomic potential of biochar from sewage sludge is examined based on macronutrient content (TOC, TN) and nutrient status (P, K, and MC).

During the experiments, it can be established that an increase in the final pyrolysis temperature of the examined sewage sludge causes a decrease in the yield of the solid fraction of biochar and an increase in the gas fraction, while the liquid fraction remains almost constant. However, the effect of the heating rate (intensity) is important only at low final pyrolysis temperatures, and almost negligible at temperatures higher than 650 °C.

At low temperatures, increasing the heating rate favors cracking reactions, as a result of which the concentration of light compounds in the liquid phase is higher, at temperatures above 650 °C the effect of the heating rate is not significant. The calorific value of the organic fraction of liquid pyrolysis products is similar to that of some conventional fuels when the energy products produced during pyrolysis are used as fuel. For this reason, there is a great possibility that these products can be used either locally, to ensure the operating temperature of pyrolysis, or as fuel for pre-drying. The toxicity of the produced biochar was examined through the total concentration of heavy metals. The temperature of pyrolysis strongly influences the physico-chemical properties of biochar and the transformation of organic elements into mineral stable forms. This is especially true for biochars produced at higher temperatures (450 and 650 °C) (SZI-4 and SZI-6). The results of the paper show that biochars generally have a minimal but lower concentration of heavy metals compared to the feedstock, especially the biochar produced at 450 °C (SZI-4). Therefore, pyrolysis of sewage sludge at 450°C (for 40 min, maximum 50 °C/min) is recommended. Although the effect of pyrolysis temperature on the concentration of heavy metals showed a different pattern for each element, showing a lower level in the case of biochar produced at 450 °C (SZI-4).

As a result, it can be said that 450 °C is the ideal pyrolysis temperature for the safe reuse of sewage sludge as a soil amendment. By extracting and recycling the organic matter content of biochar produced from sewage sludge, it represents a serious value by restoring the Earth's geo-biochemical cycle. For agriculture, they serve as organic material, plant nutrients, easily usable materials, by-products or secondary raw materials for other products.

In the case of agricultural utilization of sewage sludge, it is also important that the nutrients are not only “there,” but also accessible, in as large a proportion as possible. It is not incidental that the presence of other substances permitted by regulation, such as heavy metals (and, for example, toxins, pathogens, other organic pollutants) should be minimal. The composting process is able to keep all of this at the expected and permitted level, and control it chemically and biologically. In addition to the nitrogen, phosphorus and partly potassium active substances, municipal sludge provides micronutrients, and there are many methods for their treatment. The growing amount of sewage sludge is causing more problems, the solution of which cannot wait, since the amount of sewage sludge is constantly increasing.

The utilization and disposal of sewage sludge by composting is one of the possible and most widely used solutions to the aforementioned “problem.” In addition to plant nutrients, the by-products used as carbon sources and additional micro- and macro-elements, as part of the bio-geochemical cycle. According to the social aspects of the paper, it offers a solution for the conversion of domestic sewage sludge into biochar by pyrolysis, and additional energy products represent a promising alternative for reducing the amount of domestic sewage sludge and using it as soil improvement material. and fertilizer.

For further tests, it is recommended to carry out an examination of the drug, hormone, and pesticide residues left in the biochar, as well as the formation of free radicals, and the fact of the degradation of microplastics must be verified.

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Shifting Toward Resource Management in Remote Area: A Case Study of Lake Toba, Indonesia

13

Miwa Tatsuno and Premakumara Jagath Dickella Gamaralalage

Abstract

The Indonesian government has been making an effort to boost the local economic growth through the tourism industry in the Lake Toba region, North Sumatra, because the region has highly valuable natural and cultural assets which can attract both domestic and foreign tourists. However, proper waste management has not been established and uncontrolled waste pollutes the areas, which diminish the value of the regions as tourist destinations. With the urgency for tackling such challenges, the waste management pilot project was implemented to establish the Resource Recovery Centre (RRC) adopting the function of waste bank, as part of the practical implementation of the waste management strategy that newly developed by the local regencies. This case study aims at documenting the experience and the potential of the waste bank system in the region to shift towards resource management. Key lessons were that the waste bank system should be established as part of the overall waste management system. It helped in changing the waste management practices from linear to circular systems. In addition, this case study showcases that waste banks have made remarkable positive impacts at local or neighbourhood levels, especially, in terms of improving local residents' waste management practices and awareness, environmental protection and additional income generation by selling the separated waste materials. However, the success of the waste bank system in remote and rural areas largely depended on the accessibility to the primary and secondary recycling markets.

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Keywords

Waste management · Waste bank · Remote area · Lake Toba in Indonesia

13.1 Introduction

Lake Toba in Sumatra, Indonesia is the largest volcanic lake in the world. According to the "Toba catastrophe theory", the lake was created around 75,000 years ago following a super volcano eruption on Sumatra Island. A vast amount of ash and gas enveloped the entire Earth, and triggered a "global winter" effect, causing the average global surface temperature to fall by 3–5 °C. The size of the whole human population plummeted to less than 10,000. It was discovered that large areas of Asia were covered by a thick layer of ash, to a depth of around 2 m in India and Pakistan (Rampino and Self 1992; Antonio et al. 2014). While there is still some uncertainty surrounding this theory, Lake Toba has become a unique and valuable natural asset from geographical, historical, and anthropological perspectives. It has huge potential for the tourism industry due to its beautiful scenery and cultural heritage (Akhmad et al. 2015). The Lake Toba area was registered as a United Nations Educational, Scientific and Cultural Organization (UNESCO) geo-park in 2020, and the President of Indonesia pledged to accelerate the development of infrastructure to promote the economic industry in this region (Cabinet Secretariat of the Republic of Indonesia 2019).

In addition to the lack of infrastructure for tourism, the region faces a major challenge on waste management. Waste generated by local households and tourist areas are not properly managed, diminishing the value of the natural assets of the lake and surrounding areas. Through the field visits, it was often observed that wastes are scattered on roads, the tourist spots including the lake sides, and so on. The field survey conducted in the selected four regencies revealed that more than 50% of the region are not covered by waste collection services, and illegal or open dumping are common practices among local residents. To improve waste management in the region, waste management strategies and action plans known as *Kebijakan Strategi Daerah (Jakstrada)* at the regency level (*kabupaten)* have been developed, based on the concept of resource efficiency, under Ministry of Environment and Forestry (MoEF's) initiative and support of Institut Teknologi Bandung (ITB) and Institute for Global Environmental Strategies (IGES) (Fig. 13.1).

In order to materialise the targets, set in Jakstrada, as one of the implementation activities, the Resource Recovery Centre (RRC) which includes the function of a waste bank was developed. The RRC was established to enhance proper waste treatment and recycling, and serves as a waste collection point, transfer station of collected waste, as well as waste treatment and recovery facility, and also aims at awareness-raising and behaviour change among local residents. Noteworthy point of this implementation activity was that the RRC was equipped with the waste bank, which was an innovative attempt to introduce waste banks into the region where waste banks or similar facilities rarely exist due to a lack of recycling chains in the

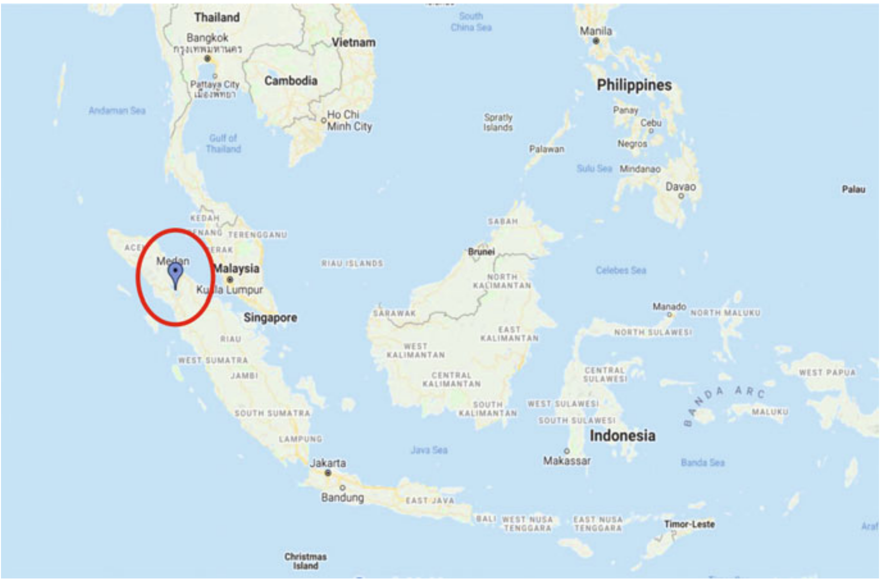

Fig. 13.1 Location of Lake Toba, Indonesia (Google map)

nearby areas. This activity was carried out by ITB, MoEF, and local municipalities, with support from IGES.

There has been a great deal of research carried out on social and economic factors, material flows, interaction with local supply chains, management, and operation, and how these have led to changes in local waste management through the function of waste banks (Wulandari et al. 2017; Khair et al. 2019). However, waste banks are set up mostly in populous urban areas where people can bring recyclables and waste banks have more opportunities to sell the collected waste. Naturally, many research studies discuss about waste banks in urban areas. On the other hand, waste banks are still scarce in rural or remote areas where waste banks have less opportunities to gain profits, and waste banks in such areas have not attracted much research studies. In such context, this paper aims at examining the benefits, challenges of the waste banks in remote areas, particularly through the experience in the Lake Toba areas, and exploring possible solutions to enhance the waste bank system as a driver for better waste management.

The present study examines the current status of waste management in the region, the background of waste banks in Indonesia and the project activities to establish the RRC with the function of waste bank. The study has been carried out through literature review and based on the findings of the field survey. The study also examines the impacts and benefits brought by the waste bank and explores the challenges. It focuses on the access issues and high transportation fee which waste banks in remote areas, where major active recycle value chains do not exist in the nearby areas, more likely to face than urban areas. In order to look at another case in a remote area, the waste bank in Gili Trawangan Island, a tourist destination island in the country, is also described. The study provides the recommendations and possible solutions for tackling the specific challenges the waste bank faces.

13.2 Methodology

Information and data were collected as follows:

A literature review and desk study for waste management issues in Indonesia and the Toba region was conducted. Then, field visits, waste survey, and a series of workshops with local residents and local government officials were organised in partnership with MoEF, the IGES Centre Collaborating with UNEP on Environmental Technologies (CCET), and ITB, from June 2019 to February 2020. The RRC with the function of the waste bank was established under the supervise of MoEF, technical advice of ITB, and financial and technical supports of IGES. Communication and interviews were conducted with the central and local government officials, local waste management experts, and local community staffs who are in charge of the waste bank operation and management. Follow-up activities were implemented to support the waste bank management in the Lake Toba region by local stakeholders, the ministries, and IGES. In addition, a literature review was conducted to explore issues of another sample case of a waste bank in remote area, i.e., Gili Trawangan Island (Table 13.1).

Table 13.1 The project activities in the Lake Toba region by MoEF, ITB, and IGES

Jakstrada development	
June–September 2019	Field work and workshop in the Lake Toba region
October 2019	• Field work and meeting with the regencies in the Lake Toba region • Survey of waste audit in four selected regencies in the region • Workshop with the province and regencies • 1st Jakstrada development workshop • 2nd Jakstrada development workshop
November 2019	• 3rd Jakstrada development workshop
February 2020	• 4th Jakstrada development workshop
Pilot project (the construction of the RRC)	
June–September 2019	Field work and workshop in the Lake Toba region
October 2019	• Determine the construction site for the RRC in Toba Samosir regency
November 2019	• Assess the construction land status • Identify the area to be covered by the service • Develop the detailed facility design • Estimate the cost • Start the construction
February 2020	• Completion • The trial running • The launching ceremony

13.3 Current Waste Management in the Lake Toba Region

13.3.1 Summary of the Field Survey

In order to understand the current waste management in the region, a field survey in the area surrounding Lake Toba was conducted in 2019.

There are seven regencies surrounding the lake, and the survey was carried out in four selected regencies, namely, Simalungun, Samosir, Toba Samosir (Although the regency's name was officially changed to "Toba regency" in 2020, the regency is referred as Toba Samosir in this article.), Humbang Hasundutan.

The field survey revealed that the estimated waste collection rates in the regencies range from 18.3% to 47.1% of the total waste generated. These low collection rates often result in illegal dumping and open burning.

The total population in the four regions is approximately 138 million, and among the regencies, Simalungun where there are major tourist destinations has the highest number. Accordingly, the regency generates the highest estimated waste, 513 (t/day), in the four regencies, followed by Samosir 88, Toba Samosir 75, Humbang Hasundutan 57. In terms of the average per capita household waste generation (kg/capita/day), Simalungun and Samosir generate approximately 0.6, followed by Toba Samosir 0.4 and Humbang Hasundutan 0.3. It is considered that Simalungun and Samosir generate higher per capita waste compared to the other two because the regencies have more major tourist destinations and commercial areas. Regarding waste composition, organic waste accounts for 44–73% in the total waste, and 10–15% are plastic in the regencies. As for the waste management, it is estimated that waste collection covers 18% of the total waste in Simalungun, 47% in Samosir, 37% in Toba Samosir, and 25% in Humbang Hasundutan. The number of waste transportation vehicles owned by the regencies is 20 by Simalungun, 37 by Samosir, 24 by Toba Samosir (No data of Humbang Hasundutan). In spite of the highest waste generation, the Simalungun regency is least covered by waste collection, and has less waste transportation vehicles than the other regencies. (Note: The capacity of the vehicles was not counted.) Regarding final disposal sites, Simalungun has one new official landfill site which was constructed in 2020, Samosir has one disposal site, Toba Samosir has two disposal sites, and Humbang Hasundutan has one disposal site and one new official site which was constructed in 2020. Landfill is defined as official site constructed by environmentally-sound design to prevent negative impact on the surrounding environment, and disposal site is defined as site where waste is disposed on open land. During the field visit, it was observed that a landfill site under construction was not properly designed and installed with proper equipment in environmentally-sound manners. For example, the pathways for leaches and soil covers were not sufficiently installed. Thus, although the landfill sites were constructed in Simalungun and Humbang Hasundutan in 2020, these sites also might have some technical defects (Figs. 13.2, 13.3, 13.4, and 13.5; Table 13.2).

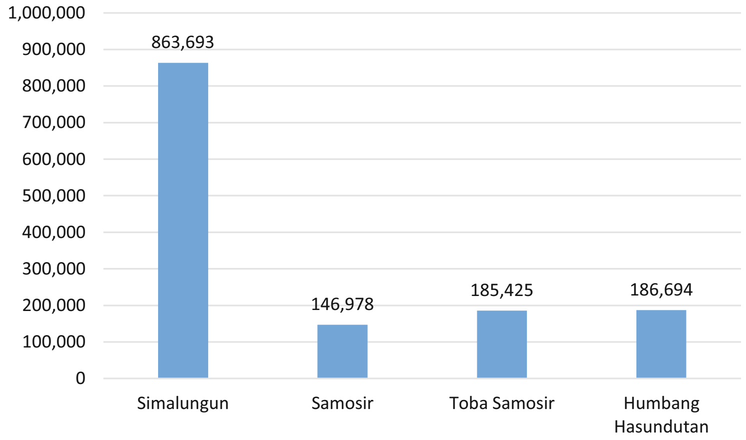

Fig. 13.2 Population in four regencies in the Lake Toba region (2018–2019) (Source: ITB research)

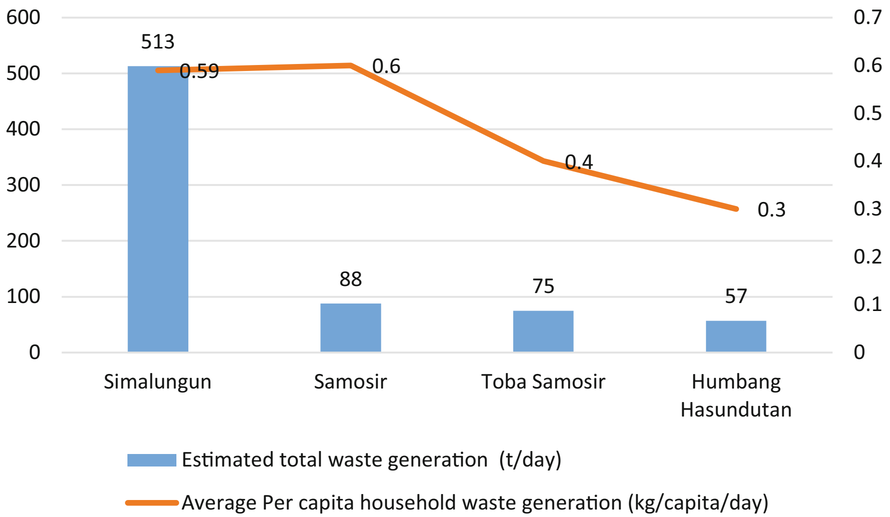

Fig. 13.3 Waste generation in four regencies in the Lake Toba region

13.3.2 Waste Bank in Indonesia and the Implementation Activities in the Lake Toba Region

13.3.2.1 The Background of Waste Banks in Indonesia

The waste bank system is the prevailing social and economic instrument to involve local communities in environmental governance, based on the 3R principle in Indonesia. Its basic idea is the same as actual banks. Customers have a money saving account, however, customers bring recyclable waste to make deposit instead

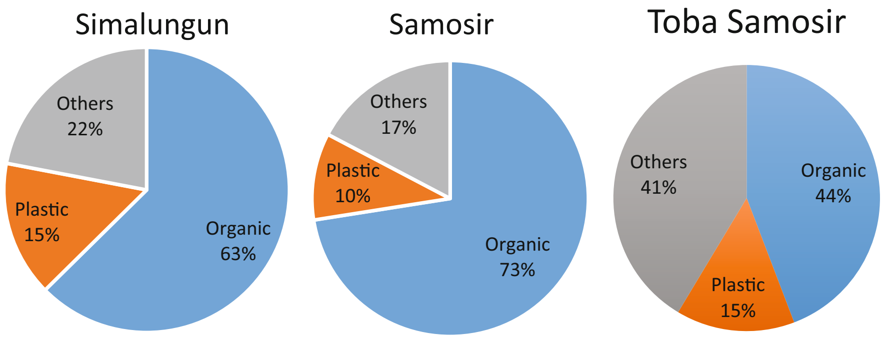

Fig. 13.4 Composition of the waste in regencies in the Lake Toba region (No data in Humbang Hasundutan) (Source: Tatsuno et al. 2021)

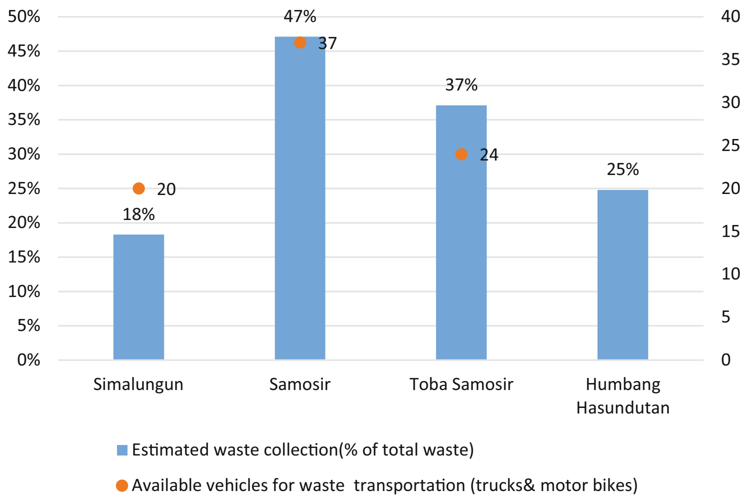

Fig. 13.5 Waste collection rates and number of collection vehicles in regencies in the Lake Toba region (Source: Tatsuno et al. 2021)

Table 13.2 Number of final disposal sites in the regencies (Source: Tatsuno et al. 2021)

Simalungun	Samosir	Toba Samosir	Humbang Hasundutan
1 landfill site[a]	1 disposal site[b]	2 disposal sites[b]	1 disposal site[b] 1 landfill site[a]

[a] Landfill site: official site constructed using environmentally-sound design
[b] Disposal site: site on open land

of money. The monetary value of the waste brought by customers are saved in their saving account. Waste banks sell the waste to recycle chains and industries and put the money into the customers' saving accounts by the sales. The system gives economic incentive for people to collect and bring waste to waste banks, and there

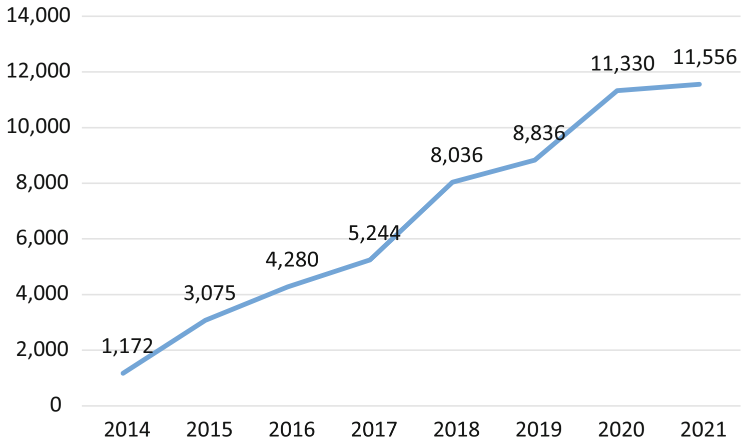

Fig. 13.6 Number of waste banks in Indonesia (Source: MoEF Waste Bank Management Information System https://simba.id/)

exist waste banks which have made notable profits as successful business, such as Satu Hati Waste Bank in West Jakarta which gains 850–1000 USD per week, in average (Purningsih 2019).

The waste bank is recognised as a proven system which contributes to reduce the amount of waste which end up in improper disposal sites including open dumping. According to MoEF's Waste Bank Management Information System, waste banks contributed to reduce 1.7% of the total solid waste generation at the national level in 2018, 2.7% in 2021, and produced 194,637.05 USD per year (MoEF, 2022).

In the context of the urgency for tackling significant waste issues, the Indonesian government encourages the installation of this effective instrument through strong policies and regulations including Ministry of Environment Regulation No. 13 of 2020 on Guidelines for Implementing Reduce Reuse Recycle Through Waste Banks (Wijayantia and Suryania 2015). The first waste bank in Indonesia was launched in Bantul, in 2008 (Wijayantia and Suryania 2015), and the system has spread widely across the nation as shown in Fig. 13.6. Around 1000 units in 2014 increased to more than 10,000 units in 2021, which means almost ten times increase in 7 years.

Since people have easier access to waste banks and waste banks can find more opportunities to sell the collected waste to recyclers and industries, many waste banks have been introduced in urban and populous areas as shown by the map in Fig. 13.7. The map shows that most of waste banks in Indonesia are located on Java Island and are concentrated in larger cities. In particular, waste bank system has been successfully established in cities such as Surabaya, Jakarta, and Bandung (Wijayantia and Suryania 2015; Unilever Indonesia 2021; Lubis 2019). On the contrary, waste banks are scares in remote areas including the Lake Toba areas.

In such context, the waste bank was introduced by the implementation activity in the Lake Toba region where there had been no functioning waste banks, as an attempt effort to change the waste management practices in the region.

Fig. 13.7 Mapping of waste banks in Indonesia (4927 waste banks in 32 provinces) (Source: https://banksampah.id/)

13.3.2.2 The Implementation Activity to Establish the RRC with the First Functioning Waste Bank in the Toba Region

As the first step toward achieving the targets in Jakstrada developed by the regencies, the RRC which includes the function of a waste bank was set up as a pilot project.

Main functions and roles of the RRC includes:

- Collect waste from neighbouring households
- Process and treat organic waste through such as composting
- Sort and clean non-organic waste, specifically saleable plastic waste
- Convert non-saleable plastic waste into oil by a pyrolysis equipment installed at the RRC

The waste treatment flow at the RRC, also called TPS (tempat pengelolaan sampah in Indonesian)-3R, meaning temporary shelter for 3R, is shown in Fig. 13.8. Collected waste are weighed by scale, then segregated manually into (1) household hazardous waste, (2) organic waste, (3) inorganic waste, and (4) plastic waste. These wastes are further processed as follows. (1) Household hazardous waste is stored at the designated area of the RRC until treatment methods are available. (2) Compostable organic waste is composted, if not, it is sent to landfill. (3) Inorganic waste is further separated into sellable plastic (Polypropylene and Polyethylene) and other sellable waste such as paper and metals. These sellable wastes are sent to recyclers after cleaning. Non-sellable plastic is processed by pyrolysis into oil. The other plastic waste which is rejected to landfilling is utilised by thermal recycling.

The management of the RRC is carried out by Toba Samosir regency with the involvement of the local community. The regency is responsible for supervising the RRC's overall management, providing a waste collection services for the local residents in the nearby areas and necessary budgets for operating the RRC including utility, and some representatives from the local community run the waste bank as a business entity to make a profit by selling waste.

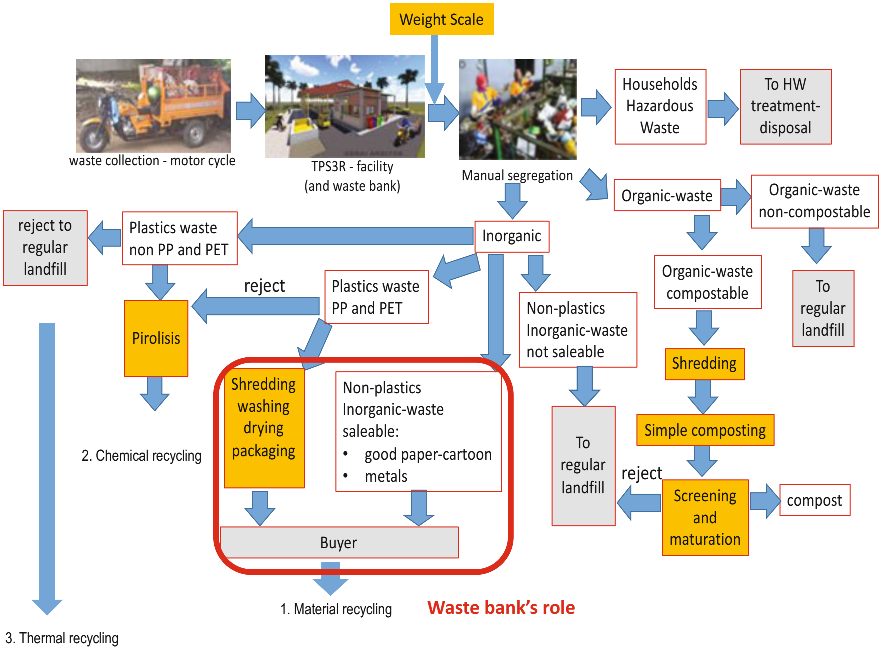

Fig. 13.8 Waste collection and treatment flow at RRC (Source: Damanhuri 2020)

The RRC with Two Unique Concepts

The RRC was designed and constructed based on the environmentally-sound concepts.

First, it basically accepts any kinds of waste including hazardous waste with the "No waste rejected" principle to prevent the rejected waste from ending up in improper final disposals including open dumping. The RRC is even equipped with a small concrete area to temporarily store hazardous waste until treatments of the hazardous waste become available. The second unique concept is its environmentally-sound and safe design of the facility. To avoid negative impacts on the neighbouring areas, the RRC was designed to prevent bad odours and noise, and to secure the safety of the RRC staffs, including the installation of the emergency evacuation routes.

13.4 Results and Discussion

This section explains the outcomes, impacts, and benefits by the waste bank, and examines the challenges identified through the waste bank's experience. In addition, in order to look at the experience of a different case in a rural area, the case of Gili Trawangan Island is also described.

13.4.1 The Impact and Benefit Brought by the Waste Bank

While the RRC has several major functions to improve the waste management in the region, this study more focuses on the waste bank attached to the RRC to see if the waste bank could be a driver for the waste management practices by local residents. Thus, this section describes the outcomes specifically brought by the waste bank, instead of the RRC overall.

13.4.1.1 The Collected Waste at the Waste Bank

In the first year of the waste bank establishment, the monthly volume of waste brought to the waste bank ranges from 637 to 8789 kg (Fig. 13.9). The spikes of the volume in some months are due to the local clean-up events organised and massive waste brought by local entities such as nearby public offices. In the 10 months from March 2020 (the waste bank was launched at the end of February 2020) to December 2020, the total waste reached almost 30 tons (Fig. 13.10). Since according to the field survey, the estimated waste generation is 75 tons/day in Toba Samosir regency where the waste bank was installed, the waste bank covers around 0.13% of the waste generation in the regency (75 tons × 30 days × 10 months = 22,500 tons). From the composition perspective, plastic waste reached almost 20 tons, which accounts for 65% of the total waste, followed by paper 23%, iron 6%, glass 3%, and metal 3%.

13.4.1.2 Attention and Interest from the Local Residents and Organisations

The number of the waste bank customer has steadily increased since the waste bank was launched. According to the local operation staffs, the waste bank has around ten new costumers per month. Although the RRC and its waste bank are on a rather

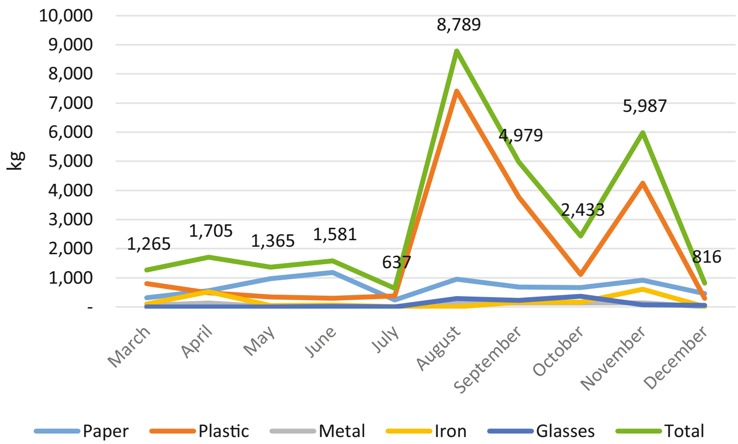

Fig. 13.9 Monthly collected waste volume at the waste bank (March 2020 to December 2020) (Source: Tatsuno et al. 2021)

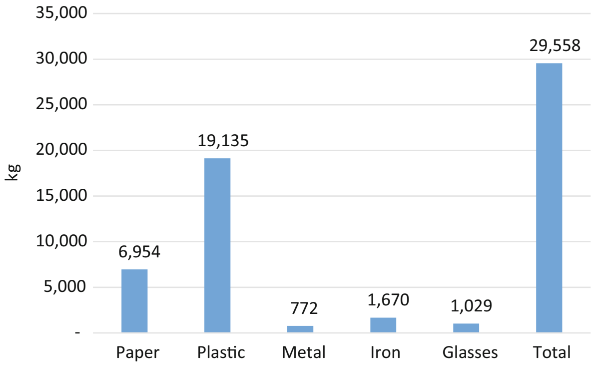

Fig. 13.10 Collected waste volume at the waste bank per category (total in 2020) (Source: Tatsuno et al. 2021)

small scale, it has attracted a great deal of attention from both the public and private sectors, including ministries and global business entities due to the remarkable attempt in the region. Besides MoEF, the Ministry of Maritime and Investment (MMI) provides strong financial and technical support. The ministry is actively assisting in public awareness activities in communities and schools and plans to replicate 100–200 new waste banks in the region in 2 years by the end of 2022. In addition, a part of the management budget has been provided by MMI.

13.4.1.3 Sales of the Collected Waste

The waste collected at the waste bank is transported and sold periodically at the nearest recycle market which is located in Medan City, approximately 100 km away from the Lake Toba and takes 4-5 hours per one-way trip. The location of Lake Toba and Medan is shown in Fig. 13.11.

According to the record of the waste bank's accounting, the sales of the waste sold in Medan in 2020 are as below. Due the COVID-19 pandemic, the collected waste had not been transported to Medan until July 2020. The total sales in the year was 2614 USD.

There was no sale of the waste from March to June in Medan while July to December, the amount earned from the sales of waste was 431, 550, 585, 308, 456, and 284, respectively, with a total earning of USD 2614 (Source: Tatsuno et al. 2021).

The monthly average sales during the 10 months in 2020 is 261 USD. Is this sales amount higher or lower compared with other waste banks in Indonesia? In the following section, its sales are compared with the waste banks in Surabaya which is the second largest city in Indonesia and one of the cities where waste banks are most prevailing in the country.

Sales Comparison with the Waste Banks in Surabaya

In Surabaya, the city has developed one of the most successful waste bank systems in Indonesia, with 180 branches in 31 local districts. Since the waste bank was firstly introduced to the city in 2010, the system has attracted many local residents to be involved as customers, with over 10,000 bank accounts made in the first 4 years

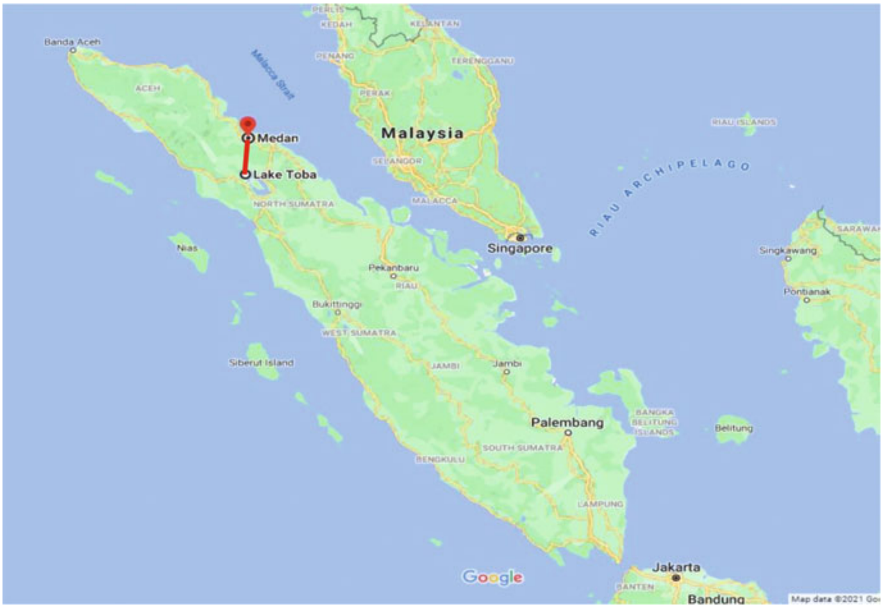

Fig. 13.11 Location of Medan and Lake Toba in Sumatra Island (Google map)

Table 13.3 Sales at waste banks in Surabaya and Toba (Wijayantia and Suryania 2015)

	Waste banks in Surabaya and Toba	IRD	Average monthly sales (USD)[a]
1	Bina Mandiri (Surabaya)	72,000,000	5142
2	Adiguna RW IX Babet Jerawat (Surabaya)	16,540,000	1181
3	Pitoe RW III Jambangan (Surabaya)	10,500,000	750
4	Daur Ulang - Balige, Toba (Toba)	3,654,000	261
5	Makmur Sejahtera RW IV Kedung Baruk (Surabaya)	2,890,000	206
6	Rukun Karya (Surabaya)	2,000,000	142
7	Untung Bersama RW V Morokrembangan (Surabaya)	1,900,000	135
8	Jepara Makmur (Surabaya)	1,600,000	114
9	Sumber Rejeki (Surabaya)	1,500,000	107
10	Bagus Karya (Surabaya)	1,000,000	71

[a] 1 USD = IDR 14,000

(Wijayantia and Suryania 2015). Table 13.3 illustrates the average monthly sales of waste at the nine major waste banks in Surabaya City, and the sales at the Toba waste bank. According to the figures, although the waste bank in Toba produces much less sales compared with the two highest-ranked waste banks, it is not particularly smaller compared with the other waste banks in Surabaya.

13.4.2 Challenges of the Waste Bank in Lake Toba and Remote Areas

Through the establishment and management of the waste bank in Lake Toba, it has been observed that remarkable impacts and benefits have been made. However, the waste bank faces several management and financial challenges. This section examines such challenges in Lake Toba, and also examines the case in Gili Trawangan Island to look at a different experience.

13.4.2.1 Far from the Market and High Transportation Fee

While Java Island has active value chains for recycling, and many waste collectors and buyers, the Lake Toba region has very limited collectors and buyers. A possible reason why Java Island attracts recycle industries is that there exist many industries and businesses which would demand recycled materials for their products and services. One of the major buyers of waste collected by waste banks is plastic recycle companies who process plastics such as PET, PP (polypropylene), HDPE (high-density polyethylene), and LDP (low-density polyethylene). For example, according to the Ministry of Industry, 87% of business entities which are involved in the plastic industry is located in Java Island. In such areas, waste banks can have easier access to the markets to sell their waste and have more opportunities to make better profits. On the other hand, for waste banks in remote areas such as the Lake Toba region, the access to the markets is one of the major challenges. For the Lake Toba region, Medan City is the nearest market for collected waste, located at a 6–7 h' drive from Toba, which incurs high transportation costs. The transportation cost during March 2020–December 2020 was recorded. There was no sale of the waste from March to June in Medan while July to December, the monthly transportation cost was No data, 139, 223, 155, 146, 125, respectively, with a total cost of USD 788 (Source: Tatsuno et al. 2021), which means the transportation cost is equivalent to 30% of the waste sales in the same period of time (2614 USD). Although the waste bank in Lake Toba can gain somewhat decent amount of sales by selling their waste, the cost for the long-distance transportation is the heavy financial burden.

The waste transportation to the recycle chains market is one of the key common logistical challenges in remote areas, and this challenge of access and high transportation cost might result in less profits, which might lower the public participations.

The Access Challenges and the Residents' Willingness to Participate

In terms of access challenges, waste banks in remote areas face the two types of access issues: (1) from waste generation at local households to waste banks or collection points (Han et al. 2018) and (2) from waste banks to recycling value chains for selling collected waste. While well-functioning waste banks can serve as a community-based waste management instrument and generate incomes for the local communities, a high public participation is inevitable for success (Indrianti 2015). These two access issues might make waste bank less attractive for people in communities, because (1) willingness of local residents to carry their waste from home to waste bank might be exacerbated by the distance to the facility (Han et al. 2018), and (2) the profits the waste bank customers could gain might be lowered due to the less opportunities to access the markets for selling their waste. Therefore, compared to urban areas such as Surabaya, local residents in remote areas more likely to have a lower willingness or less incentive to do the practices such as waste separation at source and delivering it to waste banks. Due to the less selling opportunities to the markets, conveying such practice might not always result in satisfactory income to support their daily living expenses (Han et al. 2018).

13.4.2.2 The Case of Gili Trawangan Island, an Isolated Tourist Destination

In order to look at another case in remote area, this section examines the case in Gili Trawangan Island, Indonesia, a small island which has similar three features as Lake Toba, (1) a tourist destination, (2) located far from the recycle markets, (3) insufficient waste management (Fig. 13.12).

In Gili Trawangan Island, the Bintang Sejahtera waste bank was set up in 2015 as an effort to initiate 3Rs and encourage public awareness. In the island, the main sources of waste in the island are households, hotels, and restaurants which generate 602 tons/day of waste, about 42% of which is inorganic. Proper waste management services are not provided by the local governments, and the collected waste needs to be transported to treatment facilities and the markets which are located outside of the island (Meidiana et al. 2017), which is the same challenge of the market access and transportation cost in the Lake Toba region.

The different point from the case of Lake Toba is that, due to the fairly low public participations, the waste bank has not functioned well (Meidiana et al. 2017). A questionnaire survey to local residents in Gili Trawangan Island was conducted by Meidiana et al. of Brawijaya University in Indonesia, and the survey revealed that the residents' participation in the waste bank were pretty low. In this context, they also examined quantitative measuring the effectiveness of Bintang Sejahtera waste bank by using the concrete indicators, aiming to identify the waste bank's issues, improve its effectiveness and attract public participation. Although waste banks constitute one of the nationwide efforts to implement the 3Rs in Indonesia, there is no well-established standardised evaluation methods for measuring waste banks' effectiveness. The university's research team suggests measuring waste banks' effectiveness based on the three indicators: availability; performance; and quality (Meidiana et al. 2017). These indicators are defined and calculated as below.

1. Availability: Availability is defined as the business hours of the waste bank.

$$A\ (\text{availability}) = \frac{\text{The current operational time of the waste bank}}{\text{The planned operational time allocated for running the waste bank}}$$

2. Performance: Performance is defined by how efficiently operating times are allocated and spent for each step of activities to handle waste at the waste bank. The steps include waste collection, separation, cleaning plastic waste, waste compacting, waste weighing, and data recording.

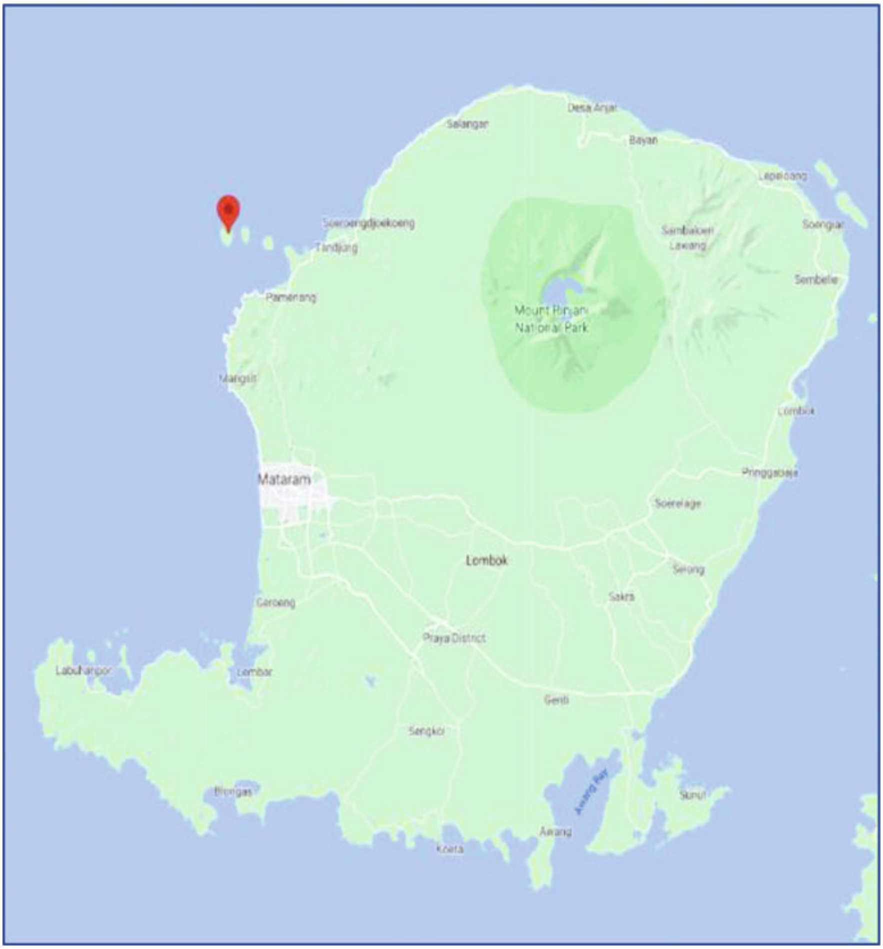

Fig. 13.12 Location of Gili Trawangan Island, Eastern Indonesia (Google map)

$$P\ (\text{performance}) = \frac{\begin{array}{c}\text{The number of waste bank's activities (sepration, compacting, weigning, and recording)}\\ \times\ \text{ideal time for each activity}\end{array}}{\text{The current operational time of the waste bank}} \times 100\ (\%)$$

3. Quality: Quality is measured based on the number of waste bank programmes successfully implemented and to what extent they have contributed to benefit the local community.

$$Q\ (\text{quality}) = \frac{\text{The number of programmes implemented}}{\text{The number of planned programmes}}$$

13.4.3 Circular Economy and Decarbonisation in the Case Study of Lake Toba, North Sumatra, Indonesia

Circular Economy is defined as follows, "Circular economy is a systems-level approach to economic development and a paradigm shift from the traditional concept of linear economy model of extract-produce-consume-dispose-deplete (epcd) to an elevated echelon of achieving zero waste by resource conservation through changed concept of design of production processes and materials selection for higher life cycle, conservation of all kinds of resources, material and/or energy recovery all through the processes, and at the end of the life cycle for a specific use of the product will be still fit to be utilised as the input materials to a new production process in the value chain with a close loop materials cycles that improves resource efficiency, resource productivity, benefit businesses and the society, creates employment opportunities, and provides environmental sustainability" (Ghosh 2020). It has been observed that the plastic waste collected in the areas of Lake Toba, North Sumatra, Indonesia are stored for a second process of production of fibre and other products using the waste collected which reaches at the end their life cycle for the intended use. For making the fibres and other recycled plastic products, the amount of virgin plastic materials used as raw materials are lesser amount in comparison to a new process. This helps in reducing the extraction of natural resources. The processes created employment of the waste handlers and processors and generates local economy creating a close loop system of regeneration. All these aspects lead to reducing the carbon emission from the related processes. Hence, the initiative of the Lake Toba, Medan, Indonesia promote the implementation of circular economy concepts and help in decarbonisation.

13.5 Recommendations

As discussed in the result and discussion, financial issues, especially the transportation fee is one of the largest challenges in Lake Toba region and other remote areas. The first important points to consider to achieve the stable and sound financial management, are (1) how to cover the transportation cost by cutting the other operation costs, and (2) attracting commercial recyclers who can cover the transportation fee. In order to achieve these two points, the following measures for (1) and (2), respectively, are examined in this recommendation section.

Measure (1) Cut the other cost on the operation processes at the waste bank by enhancing the efficient operations.

Measure (2) Increase the quantity of the waste collected by the waste bank through replicating and expanding the waste bank networks in the region. It could attract larger commercial recyclers who can cover the transportation fee to purchase the waste.

As for Measure (1), the first step is to understand the current operation status to find what weak points and bottlenecks exist at which processes. As the research team of Brawijaya University measured the effectiveness of waste banks by concrete indicators, the proposed indicators would guide and help to understand the situation of the Lake Toba waste bank, as well as to ascertain how financial and human resources should be allocated to enhance the efficiency of the management. Thus, the situation of the waste bank in Lake Toba is discussed along with the indicators.

13.5.1 The Effectiveness of the Waste Bank in Lake Toba and Suggestions

Since there are uncertainties and lack of data about these indicators for the Lake Toba waste bank, the equation developed by the university cannot be directly applied to calculate the figures for the Lake Toba case. However, looking at the current situation along with these indicators would assist understanding its current management effectiveness, and to consider solutions for the identified issues. In order to conduct quantitative evaluation on the waste bank, it is recommended to obtain the necessary data in the future.

1. Availability: The waste bank in Lake Toba operates from Monday to Saturday (around 9:00 to 17:00). The business hours give the local residents enough time to access the waste bank.
2. Performance: Through the interview with the local government officials, it was found that staffs of the waste bank spend many hours and much labour on cleaning dirty plastic waste, which is a major bottleneck to prevent efficient processes of the waste bank operation.
3. Quality: As for the waste bank in Lake Toba, because of the active support from both the public and private sectors, several remarkable activities were conducted including the large-scale cleaning-up activity as one of the government-led campaigns and the launch of the local environment youth group with the support of MoEF. Due to such efforts and strong supports from the government and other stakeholders, the number of the waste bank's branches is increasing, and according to the local government officials of Toba Samosir regency, larger scale storage for plastic waste is under construction to scale up the waste bank activities. This storage will be able to receive plastic waste from other regencies as well. As such, the positive impact generated by the waste bank in Lake Toba has been rippled in the area.

Considering the above status of the current status, the recommendations and suggestions for the issues and opportunities identified through the three indicators are discussed.

1. Availability: Setting the scheduled date and time for collection, deposit, and selling would more enhance the efficiency to handle the customers and waste collectors, etc.
2. Performance: Since one of the key factors for success of waste bank is that the waste bank customers to convey proper waste management practices including waste separation, the education programmes should be provided to teach that cleaner waste have higher economic value and to reduce the staffs' work for cleaning waste.

In terms of reducing staff's tasks, digitalisation is one of the potential options, and the successful experience is introduced here.

13.5.2 The Digitalisation of the Work Flow

Recent notable innovative operations for waste bank include employing the digital platform, and such digital applications are now actively being developed to support waste banks (SCG news channel, n.d.). In this context, there is a remarkably successful case in Bali. The waste bank called "Griya Luhu" established in Bali, 2020 provides the digital application platform where the customers can use the mobile application for all the transactions (Fig. 13.13). The application enables the customers to check their balance in their accounts and the waste prices based on the present market, withdraw the saving, and so on. Since all the data is stored and synchronised with the application platform, the operation staffs of the waste bank no longer are occupied with the manual administrative works. Furthermore, such digital platform makes the banking transactions including selling and buying waste more transparent and accountable.

As of 2021, the next year of the establishment, the Griya Luhu waste bank has 150 branches and 4000 customers. The waste bank handles more than 13 tons waste per month, and the Griya Luhu Central Bank currently produces the net profit 142 USD per month. The waste bank's profits cover all the operational costs (Yeniari and Wardimas 2021).

In the case of Toba, a digital payment software company approached the waste bank to offer their services for banking transactions. Although the waste bank did not take the offered option at the time, collaborating with such digital tech companies is one potential way to make the operation more efficient by reducing the administrative operation tasks, to increase customers' satisfactions through more comfortable and convenient tool, and to attract more potential customers. While Griya Luhu waste bank has 150 branches and 4000 customers, the waste bank's operation is covered by only eight staffs and one driver (Yeniari and Wardimas 2021). The digital tools could enable waste banks to handle a large number of customers and waste with only a few staffs.

3. Quality: As mentioned, the waste bank contributes to benefit the local community, and the waste bank networks and its capacity have been expanding among

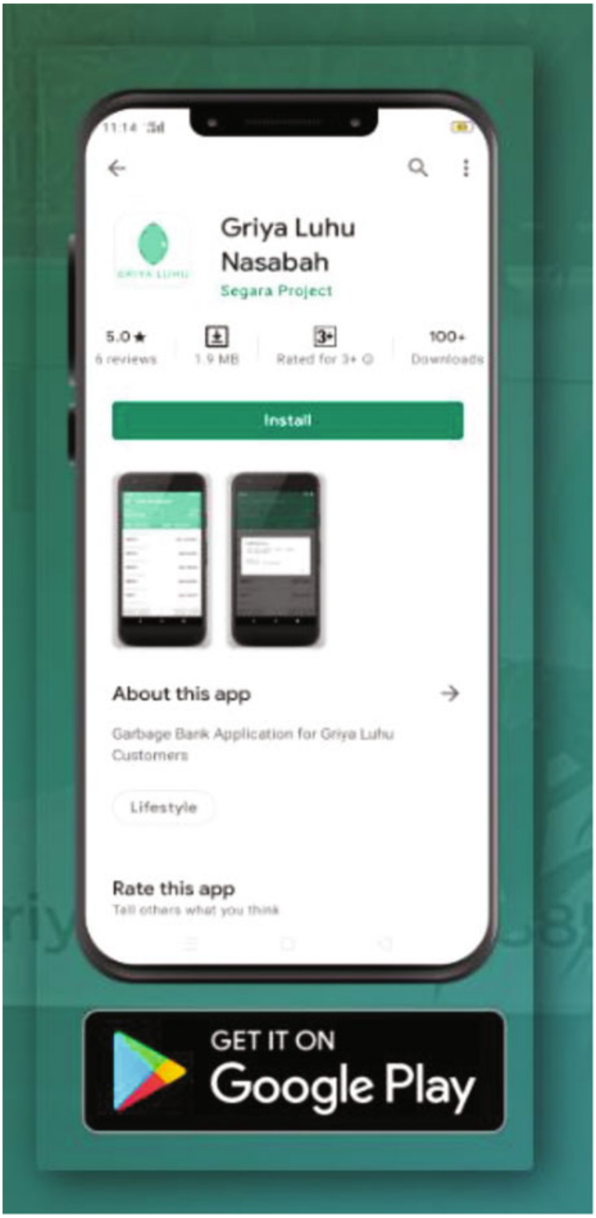

Fig. 13.13 The Griya Luhu application (Source: Griya Luhu https://griyaluhu.org/)

the local communities. How to reach and involve the local residents to expand the waste bank system is the key factor for the measure (1) raised at the beginning of the Recommendation section, (2) "Increase the quantity of the waste collected by the waste bank through replicating and expanding the waste bank networks in the region". Small amount of waste collected by waste bank often does not attract the attention of commercial recyclers. In order to gain the larger amount of waste from the waste bank system for attracting commercial recyclers, the active public participation is one of the inevitable factors. The following part discusses how the active public participation can be encouraged.

13.5.3 The Encouragement of the Public Participation

The key factors include (1) the education for the public and (2) the economic incentive.

13.5.3.1 Education

As emphasised in numerous research articles on waste banks, the education of the public plays a key role. The correlation between education and willingness to participate (WtP) is discussed here. According to the research by Han et al. (2018) on public WtP in waste management activities in rural areas, it was observed that WtP was significantly enhanced by increasing public recognition on environmental conservation and pollution issues, as well as by raising awareness on the necessity for proper waste management to mitigate the environmental issues. Such improvements on WtP were observed regardless of the socio-economic factors such as income level, gender, and age (Han et al. 2018).

In the case of Lake Toba region, according to a local public officer of Toba Samosir regency's environment office, many local residents still do not fully recognise the natural and cultural high value of the Lake Toba area, the importance and necessity of proper waste management and practices, how it would contribute to protect the environment, which could consequently result in the regional economic growth by attracting more tourists. Therefore, besides the proper waste management practices, it is important to educate local residents about the natural and cultural value of the region, the potential of the area as tourist destination, and to make them recognise the economic loss incurred by environmental damage by improper waste management.

13.5.3.2 Economic Incentive

Higher deposit amount that the waste bank customers could receive becomes a stronger economic incentive for local residents to participate in the waste bank system. Although the waste sales and deposit amount per unit fluctuate depending on various market factors, securing certain satisfactory amount of deposit to be paid to the customers should be one of the key factors to attract public participation.

In the case of the Lake Toba waste bank, according to its accounting record, the amount of the waste brought to the waste bank in the first 2 months since the launch in March 2020 are shown in Fig. 13.14. The total collected waste was 3980.5 kg, and the total deposit paid to the waste bank customers was around USD 270, which means that the deposit is around 7 cents (USD 0.07) per kg in average in this period of time.

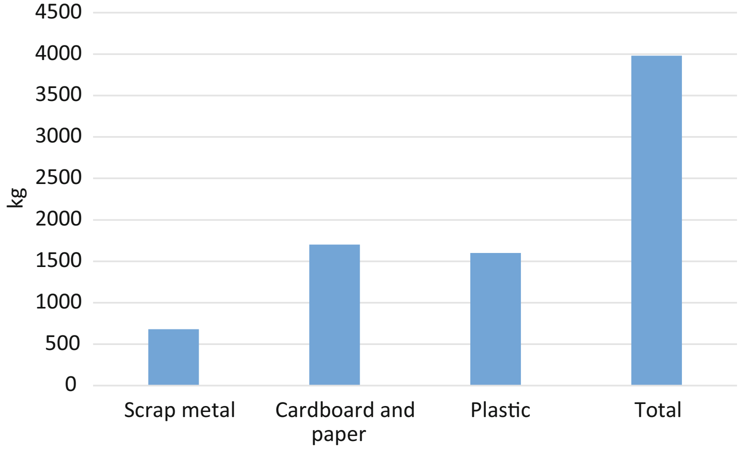

Fig. 13.14 The waste collected at the waste bank in the first 2 months

In order to understand what price range will incentivise the local residents to participate in the waste bank activities including collecting and bringing their waste, conducting a survey to research such acceptable or motivating deposit amount range should give a better consideration for making a stronger economic incentive by the waste bank.

13.6 Conclusion

In the Lake Toba region, the waste bank has attracted considerable attention from the government sectors, businesses, and local communities, in spite of rather small scale. Although its economic profit is not large, the social impact was remarkable, especially, in terms of the publica awareness and behaviour changes. The Toba waste bank showcases that even the small-scale instrument can be a strong driver for the better waste management in remote areas. It created and expanded the new norms of behaviours and mindsets among the society. Although the region is isolated from the active recycle markets and the transportation fee burdens the financial status, the more the waste banks are replicated and expanded in the area, the more opportunities it has to access the recycle value chains, or even such chains could be established inside the area. Besides the financial management, one of the key social factors for the success and long-term sustainability is to keep attracting the public participation. As seen in the Gili Trawangan Island case, the low public participation ends up in the disfunction of the system. Fortunately, the Lake Toba case has strong advantages that the national government has strong interests and pay much attention to the region due to its large economic potential as a tourist destination. The government provides the large financial support for developing the infrastructures in this region. By using that momentum, the waste bank in Lake Toba should keep sustaining the public participation through providing the attractive financial and social services and activities including educational programmes and digital technologies to the local residents to provoke their both economic and social incentives.

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Circular-BioEconomy Through Anaerobic Digestion

14

Prasad Kaparaju, Nilay Kumar Sarker, Tirthankar Mukherjee, and Sunil Herat

Abstract

Global warming and the rapid depletion of natural resources raised concerns about our traditional method of economic activities. Many ideas and models about resource-friendly production and consumption have been developed and experimented with. One of the models, circular economy has gained traction as it promotes efficiency in the utilization of resources. The circular economy is an open concept, it is still being developed. Attempts have been made to adopt a circular economy in many fields. In this chapter, we explored the circular potentiality of the anaerobic digestion system. We studied the status of bio-hydrogen and bio-methane production using different types of organic wastes and two circular anaerobic digestion models: Co-Digestion of Various Organic Wastes and Utilization of CO_2 Emissions from Anaerobic Digestion. It was found that anaerobic digestion can bring organic wastes into circularity by using it as feedstock to produce bio-methane which can replace a significant amount of fossil fuel to produce electricity and liquid transport fuel, as well as can create jobs and the digestate can replace fertilizers; combinedly these features reduce CO_2 emission too. Although bio-hydrogen showed technical potential, this technology is still in the laboratory phase. We attempted to justify our study with relevant case studies. Finally, we discussed the challenges and prospects of anaerobic digestion as a tool of the circular economy. A successful commercial circular anaerobic digestion system needs to address several key technological aspects. As it has a great deal with waste management and circular economy requires the active involvement of every stakeholder, socio-political challenges should be addressed with equal importance.

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Keywords

Circular economy · Bioeconomy · Anaerobic digestion · Microalgae · Co-digestion

14.1 Introduction

Traditional economic activities follow a linear consumption model—at one end extraction or collection of fresh resources as raw materials, then processing products for consumption, and at the other end dumping the waste. With rapid industrialization and urbanization, consumption trends also increased rapidly, and so do resource extraction. But our planetary system has circumscribed resources, and confined capability to accumulate the produced wastes (Bonciu 2014). The current trend of consumption has led us to experience global warming. The traditional economic model is also responsible for deforestation, environmental disasters, and the disbalance of biodiversity in many parts of the world. The current economic model cannot support the sustainability of economic growth in the future. Sustainability has become a major concern for both public and private sectors. Many industries have tried to adopt innovative approaches in past decades to reduce waste and increase the efficiency of their production system, some industries also tried to develop environmentally friendly supply chains (Dey et al. 2019). Recently, mainstream industries have tried to get align with new business models to achieve sustainability, such as closed-loop supply chains, reverse logistics (Govindan and Soleimani 2017), supply chains backed by environmentally friendly directions (Zhu et al. 2010), and innovation strategy to support sustainability (Klewitz and Hansen 2014). Philosophically these approaches are efficiency-oriented, CLSC, RL, environmental-oriented supply chain cooperation, and sustainable-oriented innovation are responsive-focused (Dey et al. 2020). These approaches prioritized higher environmental and social performances over economic which made them cost-intensive. The concept of circular economy was introduced to bridge this gap. To make the society transformative to adopt sustainability by getting involved all the stakeholders, circular economy conceptually creates an optimization of business factors. i.e., economic, environmental, and social issues.

Circular economy was conceptualized based on 3R principles. 3R stands for reduce, reuse, and recycle. Reduction of necessity is more applicable to individuals. Productive sectors always try to reduce their needs for decades because it reduces production costs. Innovative ideas to adopt reuse and recycle in industrial processes are the major principles to implement circularity in industrial systems. Many studies elaborated on 3R for different fields. Such as Prieto-Sandoval et al. (2018) described the traditional business model as take, make, and distribute and suggested an elaborated 3R, i.e., take, make, distribute, use, and recover to convert to circularity (Prieto-Sandoval et al. 2018). In their study, "take" was described as the raw material acquiring process, "make" as processing raw materials to products, "distribute" as to reach the products to the end users, "use" as the consumption of goods and/or services from the products manufactured, and “recover” as facilitating management of the end-of-life state of the product through reuse and recycle.

Worldwide nations and authorities are leaning towards the circular economy and attempting to form policies and regulations to bring the circular economy into practice (Yadav and Samadder 2018). Innovative approaches to a circular economy are beneficiary for the environment as it turns wastes into value-added products as well as create jobs. The circular economy has drawn the attention of national and municipal authorities because of its capability of creating jobs as well as managing waste which is a major urban concern in many medium and large cities around the world.

Although industries prefer reusing and recycling as their sustainable approach, reusing every type of waste is not feasible in the field of waste to value-added products. Sometimes recycling is the only viable option to process waste. Till now producing “any” potential products from waste is difficult. The current way the wastes are collected or disposed of does not ensure the commercial quality of being used as raw materials for many processes where the quality of raw materials is maintained strictly. Therefore, the viable options are narrowed down to a few processes. One of them is producing energy from waste.

Among the wastes produced every year, large portions are organic solid wastes. But to date, organic solid waste management is challenging in most developing countries and several other developed countries for its limited allocated budgets and lack of infrastructure. But the most challenging factor is the implementation of a management system that would be technologically viable, socially admissible, and legally justified and also should not be a threat to the environment. Organic solid wastes are managed in the traditional way, such as landfill, incineration, and composting. Organic solid wastes consist of animal wastes and municipal and agricultural wastes which are biodegradable. They are rich in proteins, minerals, and sugars and can be converted to green energy (Hagos et al. 2017). Every waste processing technology has its advantages and drawbacks. Biological treatment technologies are receiving more attention because they require lower operational energy, lower installation, maintenance, and operational as well as offer a high organic removal rate last but not least, the philosophy of the technology aligns with the circular economy (Siddique and Wahid 2018). In this chapter, we will discuss the potential contribution of one such biological process to a circular economy, anaerobic digestion (AD).

14.2 Global Generation of Organic Solid and Liquid Waste

The increase in population and rapid spread of urbanization and industrialization leads us to higher consumption of resources and products which directly contributes to the massive generation of waste. Every year, waste generation is increasing proportionally. One study projected that yearly municipal solid waste generation can reach up to 2.2 billion tons by 2025, while it was 1.3 billion tons in 2015 (Zhou and Wen 2019). It was also projected that municipal solid waste can go up to 9.6

billion by 2050 (Chatterjee and Mazumder 2019). Waste generation follows certain patterns. Such as, overall waste generation largely depends on the overall economic condition and population of a particular region or community. One study reported that per capita waste generation in urban areas of Europe and Asia was higher than in rural places (Wainaina et al. 2020). Industrially developed countries generate more waste than developing countries. Germany and France produce 6–8 times more waste than Slovenia (Wainaina et al. 2020). Because of the changing socio-economic conditions, people are moving to urban localities. A study suggested that more than 80% population of developed countries and 60% population of developing countries live in urban areas and the percentage of the rural population will continue to decrease (Silva et al. 2019). This rapid urbanization possesses a potential threat to negatively affect land use changes and infrastructural changes. Strategic changes are required to combat this effect. One potential strategy can be converting waste into value-added products. One assessment showed that the urban waste collection market worldwide has the potential to generate over $400 billion in income annually (Wainaina et al. 2020). But till now, only a fraction of these wastes are recycled and reused. Energy production from waste can be an effective approach to waste management. But till now, converting “any type of waste” into energy is not commercially feasible. Successful commercialization of waste to energy requires long and short-term plans. Long-term plans should consider the commercialization of successful laboratory and pilot-scale waste-to-energy technologies, such as pyrolysis and gasification. Short-term plans should aim to increase the commercial viability and effectiveness of new technologies, such as biogas generation using anaerobic digestion. A significant percentage of the generated wastes are biodegradable organic wastes such as food and kitchen wastes, agricultural residues, and other biodegradable solid wastes. Anaerobic digestion can be a great tool to reuse biodegradable wastes and reduce fresh resource consumption for energy production. Wastewater also contains huge amounts of biodegradable organic substances which can be used in anaerobic digestion for biogas production. Among the various types of wastewater present globally, dairy wastewater, brewery wastewater, and food processing wastewater are the most organic-rich wastewater. The European dairy industry produces around 160 million tonnes of milk and thus this industry has rich effluents containing ideal substrates for anaerobic digestion.

14.3 Current Scenario on Anaerobic Digestion from Solid and Liquid Organic Waste

14.3.1 Bio-Methane Production from Anaerobic Digestion

AD is a process where microorganisms sequentially break down complex organic substances into simpler compounds with Methane (CH_4 and CO_2) as the main products. Figure 14.1a illustrates the four major steps (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) in an AD process via which biomass is converted to bio-methane. AD technologies have been commercialized around the world.

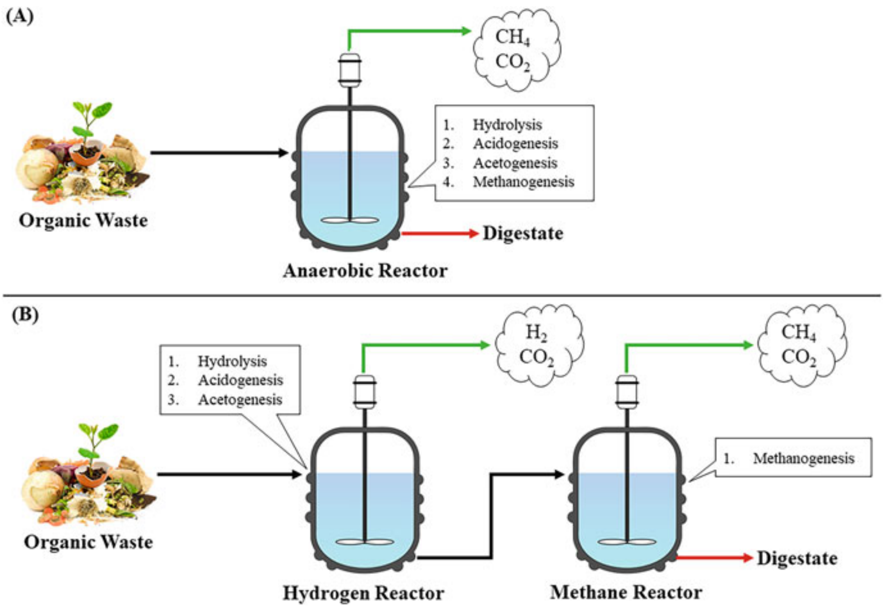

Fig. 14.1 Schematic representation of (**a**) bio-methane production. (**b**) Bio-hydrogen production from anaerobic digestion

However, because of supportive federal policies and regulations, the implementation of AD technologies happened more in Europe. Many European governments offer financial incentives to renewable energy producers (Linville et al. 2015). One study reported in 2015 that in the USA, UK, Germany, Denmark, and Australia the number of installed or commissioned biogas plants was 1497, 557, 9545, 114, and 78 (Edwards et al. 2015). To date, Germany showed the highest success to employ AD technology at a different scale. Several factors were responsible to make it happen, the main factors were support and incentives received from the government and the utilization of high-tech AD technologies. This industry has created over 40,000 new jobs in Germany and is responsible for around 40,000 m^3/h biogas utilization (Auer et al. 2017). In the UK, AD technology converted farming wastes and wastewater to biogas which was used to generate 10.7 TWh of electricity annually and created more than 3500 jobs (Torrijos 2016). In Denmark, commercial biogas plants were mainly centralized AD and produced biogas from manure, industrial organic wastes, and energy crops (Wainaina et al. 2020). The largest biogas plant in Denmark had the annual capacity to treat 54,000-ton wastes to produce biogas for electricity generation, natural gas grid, transport fuel, and heating purposes. Agricultural wastes are readily available in rural areas. Because of the poor waste management system, rural authorities consider it a huge burden. Common practices are that agricultural wastes are left somewhere to rot or they are burned in the open air. Both practices cause environment pollution. AD installed in rural areas can utilize the agricultural wastes. But taking initiations of installing commercial

ADs in rural places is neglected till now. Only China made progress on it. Till 2012, it was reported that around 30,000 large and medium-scale biogas plants were installed in rural China where agricultural wastes were used as the feedstocks (Chen et al. 2012). In Singapore, co-digestion biogas plants were installed to produce electricity. Its capacity was 40 tons/day. In this plant, different types of wastes such as horticulture wastes, animal manure, and sewage sludges were the main feedstocks (Ng et al. 2017). In the USA, farm-scale plants produce biogas from manure for decades (Linville et al. 2015). Now policymakers are pushing wastewater treatment plants to produce biogas from their wastes. A study suggested that if support is provided, more than 11,000 AD can be integrated with wastewater treatment plants which can provide electricity to 3 million households in the USA (Linville et al. 2015).

14.3.2 Bio-Hydrogen Production from Anaerobic Digestion

Bio-hydrogen can be obtained from an AD process if the four stages are divided into two reactors. As represented in Fig. 14.1b, in the first reactor only the first three stages take place (hydrolysis, acidogenesis, and acetogenesis) which produce Hydrogen while in the second reactor, only the last stage, i.e., methanogenesis takes place which is responsible for methane production. A study published in 2016 reported annually 50 million metric tons of hydrogen production (Bakenne et al. 2016). Around three-quarters of this amount was obtained from natural gas and naphtha oil, around 20% was obtained from coal and less than 5% was produced from renewable resources (Bakenne et al. 2016). Till date, anaerobic digestion does not have any contribution to commercial bio-hydrogen because of several reasons. Such as lack of suitable sustainable substrates, lack of optimized process parameters and optimized photobioreactor design, and economic challenges (Khan et al. 2018). The current status of scientific progress on anaerobic digesters to produce hydrogen commercially is still far from practice. Laboratory studies already proved the technical feasibility of hydrogen production. However, more research projects should be carried out to find out process optimization, pretreatment conditions, and chemical additives to increase hydrogen production (Khan et al. 2018). Research projects those can draw attention of investors and policy makers, such as, feasibility studies, economic assessments and life cycle assessments of bio-hydrogen production using anaerobic digester should be carried out more. Till now, the studies are directed only toward hydrogen generation from specific substrates. The type of substrate used in an experiment determines the design parameters, such as how the bioreactor should be, what should be the process parameters, and how to extract. A generic anaerobic bio-hydrogen production model needs to be formulated that can utilize a wide range of raw materials with different carbon content.

14.3.3 Liquid Digestate Production from Anaerobic Digestion

The type of substrate (feed) and digester factors such as pH, organic loading rate (OLR), hydraulic retention time (HRT), and temperature influence the digestate composition. The complete classification of the liquid digestate includes factors such as pH, organic matter, total Kjeldahl nitrogen, total carbon, total nitrogen and phosphorous, total ammonia nitrogen, total potassium, calcium, magnesium, sulfur, heavy metals, chemical oxygen demand, and biochemical oxygen demand.

Concerning the liquid fraction digestate reusability, phosphorous and nitrogen amount are vital parameters. The usage of liquid digestate for irrigation purposes was anticipated, but there are instances of phytotoxicity that were reported by Di Maria and Sisani who thus concluded that more processing is required (Sisani et al. 2022). After the solid and liquid separation of the digestate, the liquid portion contains some suspended solids and nutrients. On the other hand, owing to regulatory obligations, the liquid portion cannot be let off completely into the water bodies. There are several technologies suggested to deal with the liquid digestate like stripping, membrane technology, and evaporation. During the crushing of the substrate into the anaerobic digester, a portion of the liquid digestate can also be added. Moreover, the liquid fraction can be consumed to moisten compost piles or also as a resource for operative microorganisms to ease the composting process. The following sections discuss the usage of the liquid digestate using various methods.

14.3.3.1 Extraction of Volatile Fatty Acids

Volatile fatty acids (VFAs) are short-chain (2–6 carbon atoms) aliphatic carboxylic acids which are produced before the methanogenesis stage as intermediate chemicals during the AD process. Currently, VFAs are industrially synthesized from petroleum resources, and substituting these resources with solid and liquid wastes as the principal feedstock generates a desirable circular economy pathway. The acidification of the digestate in AD reactors is based on the optimization of operational factors, such as the HRT, OLR, temperature, and pH, in addition to using suitable methods to neutralize the methanogenic VFAs-consumers (Wainaina et al. 2019; Atasoy et al. 2018; Lim et al. 2008).

These acids contain the ability to be used as building blocks in an extensive range of industrial chemical processes. For example, pharmaceutical industries use acetic acid, paint manufacturing industries use propionic acid, perfume manufacturing uses butyric acid whereas the production of food additives uses caproic acid. The mixed VFA solution also has significant functions in wastewater treatment plants like biological elimination of phosphorus and nitrogen, biosynthesis of alcohols along with fabrication of biodegradable plastics. Furthermore, the VFAs can be employed to produce electricity in microbial fuels cells (MFC) additionally providing the carbon source for biodiesel production using bioprocesses (González-García and Bacenetti 2019).

Intending to facilitate industrial manufacturing processes, retrieval, and refinement of VFAs from the digestate is extremely vital. This comprises the crucial separation of the liquid fraction containing the VFAs from the solid substances inside the bioreactor comprising of the microorganisms and the nutrients, which may be adequate for some other applications. Nevertheless, for certain applications, more intricate separation is required for achieving precise purity conditions. Electrodialysis, gas stripping, distillation, and adsorption are examples of applicable procedures for the successful separation of the VFAs using carboxylate solutions (Atasoy et al. 2018). Some scientists have also proposed techniques with in situ product recovery of the VFAs employing membranes (Wainaina et al. 2019).

14.3.3.2 Extraction of Nutrients

AD generates nutrient-rich digestate and also lessens the environmental impact created by the wastes. The liquid digestate comprises largely the nutrients from the feed of the AD and it can be used as an organic amendment or fertilizer for agribusiness. The notable nutrients in the liquid digestate are ammonia, potassium, calcium, phosphate, magnesium, and sulfur. These valuable nutrients can be misplaced, but it is feasible to recover them via proper biochemical technologies and can be exploited as nutrient-rich fertilizers in pastoral regions for maintaining soil fertility. Thus, nutrient recovery is emphasized from the liquid digestate with least contamination load (Soobhany 2019). However, for nutrient recovery, it is a remarkably weak material in its crude form, but it can provide 9.4% of phosphorous and 5% nitrogen introduced with inorganic fertilizers independently(Chojnacka et al. 2019).

The nutrient-rich liquid digestate can be used for microalgae growth. The existence of toxic chemicals in the liquid digestate can hinder the growth of algal cells, and therefore dilution with saline groundwater, tap water, seawater, or secondary/tertiary wastewater, seems to be a favored method to dilute the raw digestate.

14.3.4 Solid Digestate Production from Anaerobic Digestion

Digestate is utilized instantly after its removal via tank trucks to transport or a system of pipelines from the anaerobic digester to the agricultural fields around the plant. Due to the high concentration of nutrients and nitrogen, the digestate is preferred to be used as a soil improver or as a fertilizer because it has a chance of nitrogen leaching and thus polluting the nearby water bodies. Modern methods in solid digestate include composting and also pyrolysis, ensuring in making of superior soil improver from the composting method and also the production of syn-gas, bio-oil, and biochar from pyrolysis. Sheets et al. described utilizing fibers from the solid digestate to make bedding material, particleboard, and cement. The following sections discuss the usage of the solid digestate using various methods (Sheets et al. 2015).

14.3.4.1 Utilization as Fertilizer

The partly stabilized solid digestate which is obtained after separating the digestate, can be exploited as a soil conditioner or a biofertilizer. Since the solid digestate still comprises some biodegradable material, odor emission can take place due to microbial activity. To minimize the environmental effect and also a lasting biofertilizer that is merchantable, additional treatments such as drying, and composting are suggested to stabilize the organic material.

The organic matter in the solid digestate is decomposed and converted during the composting procedure by microbes under aerobic conditions. Compost is a perfect biofertilizer because it gradually discharges nutrients and demonstrates decent performance as a soil improver. Furthermore, composting can increase total organic carbon, nitrogen, pH, and also phosphorous contents in the soil (Tambone et al. 2007). During this process, bulking material should be added to the solid digestate which will help air to enter the material and thus will stabilize the process. Moreover, the bulking agent has various positive outcomes in the products like enhancing the nutrient strength, reducing the electrical conductivity, weakening the heavy metal substrates, and also lowering the nitrogen content during composting.

14.3.4.2 Utilization as Pyrolysis Feed

Pyrolysis is a thermal decomposition process of organic material under an inert or very low-oxidizing atmosphere from a temperature ranging between 250 and 1200 °C. During the pyrolysis process, organic material, for instance, hemicelluloses, lignin, cellulose, and proteins are decomposed thermally to produce three main products: syngas comprised of non-condensable gases, bio-oil, and biochar (Bose et al. 2021).

The by-products from the solid digestate pyrolysis can be utilized as valuable material like biochar or as fuels such as bio-oil and Syngas. Pyrolysis typically begins from the drying process of the solid digestate. The excessive energy mandate for drying the solid digestate can be made up by the excess heat from the biogas Combined Heat and Power (CHP) unit (Monlau et al. 2015). After assessing the energy balance of both a single AD process and the combined AD followed by the pyrolysis process, roughly a 42% surge of electricity is attained in the integrated system. Monlau et al. (2015) reported that only bio-oil and syn-gas were combusted to produce energy whereas the biochar was exploited as a soil amendment. The solid digestate obtained from food waste can similarly be pyrolyzed for fuel production (Opatokun et al. 2015). The temperature used in industrial scale pyrolysis furnaces is generally 500 °C. After the solid digestate from food waste was pyrolyzed at 500 °C, the product consisted of bio-oil (major component) which accounted for about 52.2% of the total mass with a calorific value of 7.78 MJ/kg (Opatokun et al. 2015). Liquefaction of the solid digestate in glycerol and polyethylene glycol with H_2SO_4 as the catalyst enhances the bio-oil yield. The highest bio-oil production of 59.3% and higher heating value of 28.4 MJ/kg were reached after microwave liquefaction of the solid digestate (Barbanera et al. 2018).

Instead of using the produced bio-oil or aqueous liquor after pyrolysis as fuels, it can be re-utilized as a feed for the anaerobic digesters for biogas production thus integrating pyrolysis and AD (Hübner and Mumme 2015). Hübner and Mumme (2015) reported that the aqueous liquor from the solid digestate pyrolysis at 330 °C produced 199 mL CH_4/g-COD but the CH_4 yield decreased at higher pyrolysis temperatures. Approximately 56% of COD, along with most of the volatile matter, can be utilized after the AD of the pyrolysis liquor (Hübner and Mumme 2015). On the other hand, the wastewater produced from the thermochemical process (like pyrolysis and liquefaction) comprises inhibitors for example glycolaldehyde, which could have microbial toxicity (Jayakody et al. 2018). Thus, the pyrolysis liquor with inhibitors and complex organic materials might not be pumped back into the anaerobic digester because of its toxicity to the microorganisms (Hübner and Mumme 2015).

In several studies, the biochar obtained after solid digestate pyrolysis was added to the AD process to enhance the methane yield, the agronomic trait of the digestate and process stability (Peng et al. 2019; Masebinu et al. 2019). The biochar from the solid digestate pyrolysis can ease the AD process by diminishing the acid and ammonia stresses while improving the direct interspecies electron transfer. High porous biochar with Brunauer-Emmet-Teller specific surface area greater than 100 m^2/g can be synthesized from solid digestate pyrolysis at 800 °C, which will act as a support for the colonization of functional microbes inside the anaerobic digesters (Masebinu et al. 2019).

14.4 Implementation of Circular-BioEconomy Through Anaerobic Digestion

The circular economy is defined as "an economic system aimed at eliminating waste and ensuring the continual use of resources, through reuse, sharing, repair, refurbishment, remanufacturing, and recycling to create a closed-loop system, minimizing the use of resource inputs and reducing the creation of waste, pollution, and carbon emissions" (Geissdoerfer et al. 2017). In 1966, Kenneth Boulding developed the idea or concept of circularity in an economic system (Kumar 2019). The circular economy has a solid connection to the Sustainable Development Goal no. 12 of the UN 2030 Agenda for Sustainable Development specifically in Sustainable Production and Consumption (Voola et al. 2022).

A bio-based economy or bioeconomy is defined as "the production of renewable biological resources on land and water, and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products, and bioenergy" (Geissdoerfer et al. 2017).

Although resource usage and "renewable" are the main concept in a bioeconomy, and resource preservation is the inspiration behind the idea of a circular economy, a circular bioeconomy is a notion where side streams emerging from the renewable bio-resources are circulated back into the environment through conversion of matter to energy or open-closed recycling (Funduk). Whereas a circular economy, on the whole, comprises both renewable and also non-renewable resources, a well-developed circular bioeconomy solely focuses on only renewable resources which is an attractive aspect because it satisfies quite a few sustainable development goals. A non-linear bioeconomy, stressing inventing new ways for the usage of end-of-life products and also waste streams in the technosphere, and is therefore a subcategory of the circular economy. Thus both "bioeconomy" and "circular economy" might be taken into account as parts or subsections of a "green economy," which is a word that was created in 2012. A green economy includes both social well-being and impartiality along with environmental sustainability and economic growth (Stahel 2017). The extent of suggested activities in "the era of R's" in a circular bioeconomy (not restricted to only waste management) has improved over the years and now consist of "reclaim, remediate, reuse, recycle, renovate, refuse, replenish, rainwater-harvest, resilience and reverence for nature" (Vogelpohl et al. 2022).

14.4.1 Proposed Models for Circular-BioEconomy

14.4.1.1 Co-digestion of Various Organic Wastes

Co-digestion is a technique where more than one type of bio-waste is biodegraded or digested in one anaerobic bioreactor (Fig. 14.2). More than one bio-waste in proper ratios can serve as a favorable practice for enhancing product yields credited to the surplus of nutrients which increases the microbial functions along with the environmental and economic advantages of dealing with a mixture of bio-waste materials in a single facility (Díaz et al. 2011; Abad et al. 2019). Numerous researchers have examined the enhancement of AD systems utilizing various solid and liquid bio-wastes signifying that anaerobic co-digestion, is a promising technique for attaining a circular bioeconomy. An investigation conducted by Panichnumsin et al. (2010) described that a mixture of cassava pulp and pig manure in the ratio of 3:2 led to an escalation of methane yield by approximately 41% compared to the usage of pig manure alone. The probable reason for the increase in methane yield was due to the upgraded process stability in addition to an escalation in the quantities of readily degradable macromolecules (Panichnumsin et al. 2010). In a different

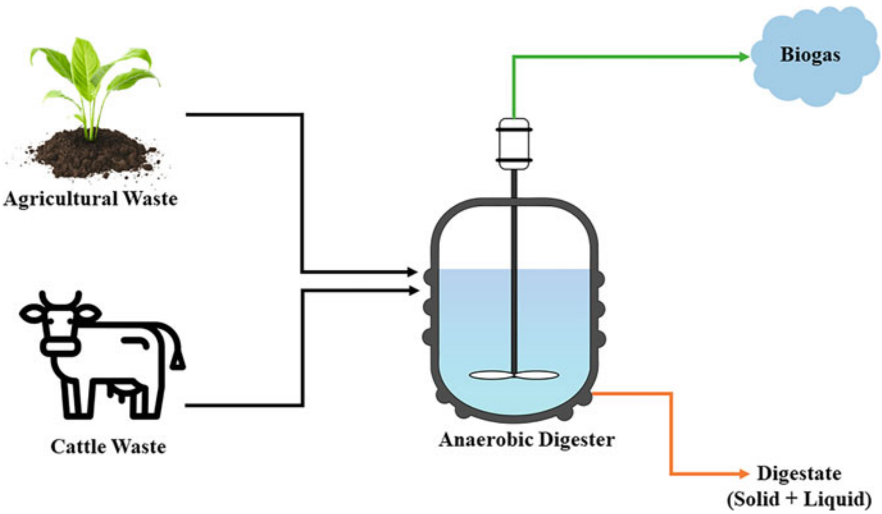

Fig. 14.2 Schematic representation of co-digestion via anaerobic digestion

report, appropriate C/N (carbon-to-nitrogen) ratio and increased buffering capacity facilitated the AD process to be stable even at a high organic loading rate and also without adjusting the pH when cattle manure and food waste were co-digested in a ratio of 1:2 which led to an increase in methane yield by approximately 55.2% weighing against food waste alone (Zhang et al. 2013). The co-digestion approach is furthermore advantageous when aiming for additional AD bio-products such as VFAs and H_2. A study done by Zhou et al. inspected quite a few mixtures comprising waste-activated sludge, primary sludge, and food waste and deduced that co-digestion of different substrates enhanced the H_2 yield compared to single the substrates. However, the maximum H_2 yield was observed when waste-activated sludge/primary sludge/food waste combination was used at a ratio of 5:15:80 (Zhou et al. 2013a). Zhou et al. also examined the effect of co-digesting corn straws and waste-activated sludge. They inferred that when both the bio-wastes were mixed in the ratio of 1:1, the VFAs production reached a maximum of up to 69% compared to waste-activated sludge only. Additional results showed that both carbohydrate and protein consumption increased by 220 and 120%, respectively (Zhou et al. 2013b). Other than the typical wet AD, solid organic wastes can be biodegraded using dry inoculum, i.e., dry microbial source at total solids (TS) content between 15% and 40% in the dry AD processes via horizontal/vertical plug flow reactors or sequential batch reactors. Dry AD is a favorable technology for areas with low availability of water and also this process requires more compact bioreactors. While using dry AD in batch process an increase of around 14% in methane production was attained when wheat straw, chicken feather, and citrus wastes were mixed at a ratio of 6:1:1 compared to the single substrates. When the same combination of substrate ratio was used in a continuous plug flow bioreactor, 362 $NmLCH_4/gVS_{added}$ was the methane yield at a loading rate of 2 gVS/L/d was achieved (Patinvoh et al. 2020). Capson-Tojo et al. also investigated the dry AD process utilizing a combination of waste cardboard and food waste in a batch approach. Their study fixated on the effect of ISR (inoculum-to-substrate ratio) which was realized to have a substantial impact on the methane and hydrogen productions, VFAs and also microbial dynamics (Capson-Tojo et al. 2017).

14.4.1.2 Utilization of CO_2 Emissions from Anaerobic Digestion

AD turns waste into green energy. But the process is not waste free, it generates digestate. Several successful examples are available of using digestate to produce biofertilizers. Biogas cannot be used directly in many commercial applications because of high CO_2, such as liquified natural gas or liquid biofuel for the transport sector. CO_2 reduces the energy content of the fuel. CH_4 content needs to be increased to above 90% for such applications. Upgrading biogas follows a similar principle to upgrading natural gas. Absorbent chemicals such as MDEA and DEA are used to absorb CO_2 (Sarker 2020, 2016). Upgrading biogas requires to require setting up a plant, which needs a high operation and maintenance cost. This makes biogas upgrading a cost-intensive mechanism. In this section, we propose a model of integrating microalgae cultivation with AD that can potentially solve many issues of the traditional biogas upgrading process by adopting a circular bioeconomy.

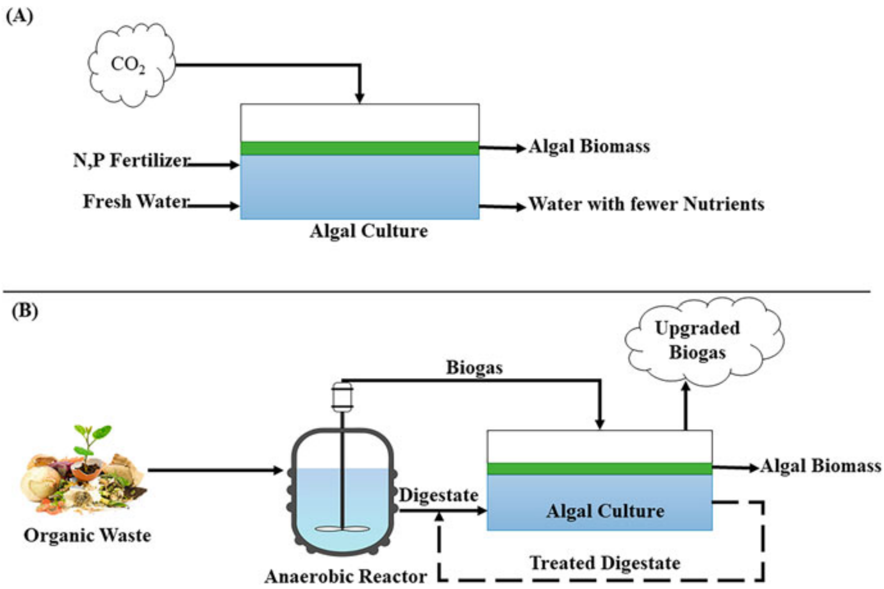

Fig. 14.3 Schematic representation of (**a**) microalgae cultivation. (**b**) AD integrated with microalgae production

Microalgae is a unicellular plant. Like plants, they grow by consuming nutrients such as N and P. They also consume CO_2 and use energy from the light like plants. Microalgae can grow anywhere if they get their growth elements (Bhadra et al. 2020). Microalgae can be grown indoors, outdoors, in closed photobioreactor or open ponds, and even in a hybrid system (Sarker and Salam 2019, 2020). Microalgae can be cultivated using wastewater also (Sarker 2021). Microalgae do not need optimized nutrient content. This is a unique feature of algae. Additionally, the biochemical composition of algal biomass can be manipulated by adjusting the nutrient composition. We propose a model of using digestate from AD to use as an algal growth medium. The digestate contains both water and nutrients. Then biogas will be fed in a closed chamber where microalgae will be grown in digestate. Microalgae will consume CO_2 while they grow and as outlet gas, we will get upgraded biogas with higher CH_4 content. More research projects will be required to optimize process parameters that will lead to upgrade biogas. Figure 14.3a, b shows simplified process flow diagrams of AD, microalgae cultivation, and AD integrated with microalgae cultivation.

Integration of AD with commercial microalgae cultivation serves circularity to both processes. In the traditional biogas upgrading process, no value-added by-product is gained. The whole cost-intensive process serves only one purpose—increasing CH_4 content. In some plants, digestates are used to produce alternative fertilizers. But the digestate processing also consumes resources. In the case of using digestate as an algal growth medium, it needs to be diluted to reduce solid concentration only. No other process is required. Biogas will be fed in the same chamber where digestate is fed. As output, we will get upgraded biogas, treated digestate, and algal biomass—all simultaneously produced in the same chamber. Digestate treatment is environment-friendly. Then the treated digestate will be used to dilute the raw digestate. It also reduces water footprint. One study suggested 1 kg of dry microalgal biomass requires 1400 kg of fresh water (Martins et al. 2018), which can be replaced by digestate. The algal biomass can be used for various purposes. Such as, protein, lipids, and carbohydrates can be extracted from the algal biomass and processed to produce fuels, different types of chemicals, cosmetics, and food supplements (Vanthoor-Koopmans et al. 2013; Wijffels et al. 2010; Chew et al. 2017; Wang et al. 2017). This algal biomass can be obtained as a by-product of biogas upgrading. It will also be helpful to save money. Integration would increase the size of the plant, but it will be less compared to the summation of individual plants. Studies suggested that, if the size of the treatment plant increase, it's per capita cost decreases (Sarker and Sarkar 2018).

14.5 Case Studies

In this section, we will discuss the capability of AD to contribute to circular bioeconomy with practical examples.

14.5.1 Case Study 1

Quasar developed an LSAD technology of 1.15 million gallons capacity with a double membrane roof for a wide range of feedstocks such as manure, FW, mixed organics, FOG, and biosolids. For this particular case study, the LSAD processed annually 15,000 tons (wet) waste consisting of 25% manure and 75% food waste at Jordan Dairy Farm in Rutland, MA, and 100,000 tons (wet) waste consisting 50% biosolids and 50% a combination of FOG, food waste, sugar water, and whey at the Wooster Water Pollution Control Plant in Wooster, OH to produce biogas. The produced biogas was used to generate 300–1000 kWh of electricity annually. Several of the systems had CNG production capabilities of 550–3600 gge/day. The AD process also produces class A or class B biosolids sold as an alternative to traditional fertilizer (Linville et al. 2015).

14.5.2 Case Study 2

CleanWorld developed a thermophilic, continuous, high-rate, and three-stage HSAD. They named the technology BioDigester. The BioDigester hydrolyzed organics in the first stage, turned hydrolyzate into methane in the next stage, and finished the mythification at the last stage. This technology generated leachate with much lower organics than other systems. Its short retention time made it possible for rapid waste feeding. First commercial HSAD system was installed in 2012 at

American River Packaging in Sacramento, CA. It processed annually around 2900 tons of FW and unrecyclable corrugated material and generated 474.5 MWh of energy and 1000 tons of soil amendment. Another plant built in 2013 at Sacramento BioDigester processed 40,000 tons of organic waste and produced 700,000 DGE/year of CNG fuel as well as 10 million gallons of liquid fertilizer and soil amendments (Linville et al. 2015).

14.5.3 Case Study 3

The project was carried out in the Fullriggaren district. The district had 614 apartments. The district was built based on the feedback on the quality of waste and its pretreatment, and social opinion on waste collection and processing, every apartment had shrunk shredder, directly connected to a storage tank. Every apartment had two drainage channels, one that was connected to the toilet went to the wastewater treatment plant. The second drainage channel, connected to the grinders was used to carry out the food waste and kitchen wastewater to a separation tank. The non-degradable elements were extracted, and the mixture was diluted by adding water or liquid food waste like sauce or juice. This mixture was added to food waste mixed with local industrial and agricultural wastes was used to produce biogas which was used to produce heat and electricity. Because of the available technology and the volume produced, most of the produced biogas was upgraded and used as transport fuel (Khan et al. 2016). Later, because of socio-political reasons, the project was closed. But still, it was successful to some extent and an example of a technologically and economically viable well-planned circular effort (Khan et al. 2018).

The first two case studies are successful examples of implementing a circular loop in a business model using AD. Biogas replaced fossil fuel and associated CO_2 emissions. Additionally, the digestates of the plants also produced biosolids, liquid fertilizer, and soil amendments, these things replaced traditionally produced fertilizer. These fertilizers were supposed to be produced traditionally, using fresh raw materials. These products replaced those requirements and also associated CO_2 emissions. In the third case study, biogas was produced from domestic wastes making houses zero waste. This case study also shows how the socio-political condition was important for the implementation of a circular economy.

14.6 Challenges and Prospects of Circular BioEconomy via Anaerobic Digestion

The development of the biogas industry in a country warrants active participation from all the stakeholders, from the federal government to end-user consumers. Creating a biogas market is just the first step, keeping it active is no less important. It needs the legitimacy of technological change. For example, China has created a big biogas market with government support. The market is backed by many biogas plants and an adequate supply of raw materials. But China is trying to establish a strong domestic biogas market. But still, they need to overcome several challenges, such as comparatively higher operation costs, experienced personnel to operate the plant efficiently, and several other missing key technologies (Zhang et al. 2019).

A lot of biogas plant using AD operates at low conversion efficiency (Zhang et al. 2019). Scientific breakthrough to enhance AD conversion efficiency is required. Based on the pilot and industrial scale studies of the past 30 years, it was found that co-digestion, pretreatments, bioreactor optimization, process, and bioreactor design optimization can be the earliest solution (Zhang et al. 2019). A commercial digester requires careful consideration to use enhancement strategies. These considerations include principle components of feedstocks and their C/N, VS, and TS; pH, temperature, OLR, and HRT of the process; factors that would inhibit the process, such as contents of heavy metal and ammonia, as well as dominant species and microbial interaction networks (Zhang et al. 2019). Co-digestion is the enhancement technique that is used most globally. Currently, a new co-digestion attempt is being tried, wastewater with food waste. Additives can be added to enhance microbial growth in AD. Using additives can be a good strategy, but their economic feasibility, the effect of scale, and environmental impacts should be studied (Zhang et al. 2019). Three-stage anaerobic digestion plant can be a subject of medium-term plans as it showed the potentiality of improved efficiency. But till now, this technology is still in the laboratory phase only, its economic and technical feasibility for commercial applications should be studied rigorously.

Although AD offers numerous benefits, this technology has to face many challenges which are not entirely related to the efficiency of the technology. One major challenge is public perception. As manures and different types of organic wastes are used, which emit a bad smell, sometimes people do not want it in their backyards. Environmental and health issues also contribute to social acceptance. Biogas contains unwanted and hazardous substances such as H_2S, Si, VOCs, CO, and NH_3 (Uddin et al. 2021). H_2S and NH_3 are harmful and highly corrosive, causing harm to combined heat and power units and metal parts (Angelidaki et al. 2018). The contents of H_2S possess a negative impact on the quality of the biogas such as reducing energy content, emitting harmful emissions, and causing corrosion (Farghali et al. 2020). Since the raw biogas contains impurities, preventative measurements should be applied to enhance methanol yields and post-treatment to eliminate H_2S. These processes are energy-intensive and require high costs (Farghali et al. 2020). Also, climate effects on biogas production are likewise to other renewable energy sources.

14.7 Conclusion

Global warming requires rapid action to reduce the emission of CO_2. But we should also consider the fact that our planet has limited resources and our current economic patterns are causing fast depletion of the resources. Only greenhouse gas emission reduction is not enough for a safe future, we must rethink our current behavior pattern on resource consumption and modify and update our behavioral pattern where it is required and relevant. The circular economy is one such novel concept that can drive us to a better future. The practical implementation of circular economy and its successful continuation depends on several external factors such as public policy, market, technical feasibility, and stakeholders, and internal factors—resources, capabilities, and competencies of the entity responsible for running the circular economy activities. In this chapter, we showed the applicability of circular practice for an anaerobic digestion system; a circular system to produce renewable energy. Successful implementation of a circular anaerobic digestion system can take us forward by ensuring reduced demand for fossil fuel, less waste to think of, and less resource consumption.

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