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MANAGING PLASTIC WASTE IN ABU DHABI: A TRANSITION TOWARDS CIRCULAR ECONOMY

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ABSTRACT

Plastics, which are organic polymer compounds, are essential products that are ubiquitous, versatile and serve virtually all sectors and industries. Plastic waste is a huge challenge, adding substantial stress to our ecosystem and affecting climate change that needs attention to be resolved. Managing plastics waste is of growing significance as feedstock material costs are on the rise, reduction in our finite resources which constitutes plastics (99% formed from Oil & Gas) and increased global awareness on sustainability and circular economy. This study examines plastic waste's detrimental impacts on biodiversity, the environment, human health, and the economy. In addition, it explores the current plastics waste management practices in Abu Dhabi. A gap assessment has been conducted to identify the major gaps for managing plastic waste and in turn, benchmark to adopt the best practices being implemented internationally (EU in specific). Therefore, developing a circular economy design model will outdo and optimize the current practices by providing oversight to the plastic value chain and creating an efficient solution. A model that is pragmatic and integrative in nature for Abu Dhabi.

Keywords: Plastic waste management, Mechanical Recycling, Chemical Recycling, Circular Economy, Sustainability.

1. INTRODUCTION

The area of focus of this paper is the Emirate of Abu Dhabi. It explores the current management of plastics waste and consequently conducts a gap assessment. Abu Dhabi's economic activities, decades ago, started with the humble pearl diving and then transitioned to Oil & Gas business and now further evolving into diversified business activities and introducing new energy mix, becoming a major technology base, sustainability pioneer and industrial champion. It is the largest of the UAE's 7 Emirates, with an area close to 67,340 km2 covering 87% of UAE land in a strategic geographic location (SCAD, 2020). It is the 1st in the Middle East in the Global Competitiveness Index, 1st in the MENA region for ease of doing business, the safest city in the world, happiest and smartest city in the Middle East (ADIO, 2020).

This research work aims to develop a pragmatic and integrated plastics waste management framework and model for Abu Dhabi. It aims to address the major challenges faced by plastic waste that are causing profound adverse impacts to the whole ecosystem from human health to the environment. Waste could be turned into wealth and valuable materials by closing the loop through Circular Economy Approach and thus diverting from the current practice of landfilling. The design aims to advance and accelerate the implementation of Abu Dhabi's Sustainability Strategies.

The design project adopts a design thinking and goal-centered approach rather than being merely technological. The goal that is aspired to be achieved is managing plastics waste in Abu Dhabi reaching Zero generation of Waste. Therefore, to reach this goal, a top-down approach is being conducted with a set of objectives defined for this research project and are broken down into the following:

1. Screen the size and scale of the issue in Abu Dhabi
2. Investigate the current Abu Dhabi Practices and conduct a Gap Assessment
3. Identifying the hazards of plastics waste (HSE Impact Assessment)
4. Evaluate alternatives and benchmark against best practices to manage plastics waste
5. Develop a Framework and Design a Circular Plastics Economy Model
6.

2. LITERATURE REVIEW

An extensive review of numerous scholarly sources on managing plastics waste has been conducted and the approach is thematic and methodological which are detailed in the following sections. The motivation of this work and description of this issue is that throughout the past decades and with the Industrial Revolution, people utilize plastics in various sectors and industries worldwide, which requires the plastics material to be durable, lightweight, corrosion-resistant and many other significant properties. On the other hand, mismanaged plastic waste poses serious health and environmental concerns. One of the major HSE concerns raised by the extensive use of plastics is the adverse impact on the environment and water, as plastics contain materials that are considered hazardous and toxic to the environment (Wu et al., 2021). It can take up to decades, centuries and even millennia for plastic waste to decompose due to its chemical structure and strong chemical bonding. Furthermore, plastics can release toxic chemicals, heavy metals and other pollutants into groundwater when placed in wet soils. They can also represent a fuel source when exposed to heat, which can eventually lead to a fire that will produce smoke containing toxic chemicals and particulate matter that poses human health consequences (Ragaert et al., 2017). Within the GCC (Gulf Cooperation Council) countries and the globe, there is an elevated number of waste plastics generated and disposed of in the area, making it a persistent matter that needs to be addressed and resolved. Thus, a holistic strategy in managing this type of waste is the optimal and recommended approach to be embraced (Stenmarck et al., 2017).

2.1 Global Plastics Production, Lifecycle of Plastics and Value Chain

With the current exponential and rapid population growth and increased economic activities transitioning to the 4th Industrial Revolution, the demand for plastics has grown at unprecedented rates. Plastics' global production in 2019 amounted to a staggering figure of 370 million metric tons as shown in Figure 1 (Khadke et al., 2021). Surprisingly, with such enormous production values of plastics, only 14% gets recycled, 14% incinerated and a striking 79% haphazardly landfilled and leaked into the environment as shown in Figure 2 for plastics waste fate and transport (Ncube et al., 2021). Therefore, polluting oceans and rivers and contaminating our soils. Figure 3 exhibits an overview of the plastics value chain from raw material production, manufacturing and use up to disposal and end of life treatment. This representation is of paramount significance as it provides an insight into the key contributors who play a crucial role in the lifecycle of plastic waste.

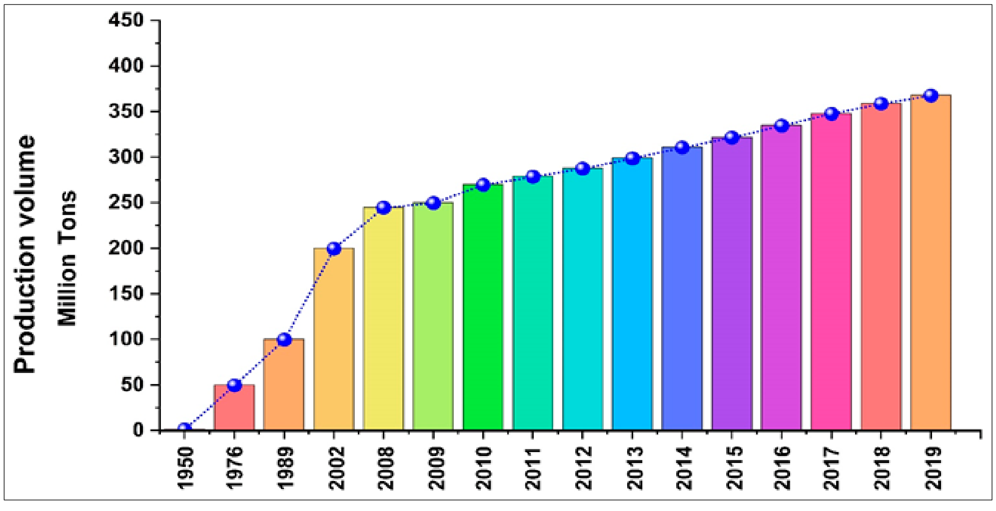


Figure 1: Global Production of Plastics from 1950 to 2019 (Khadke et al., 2021)

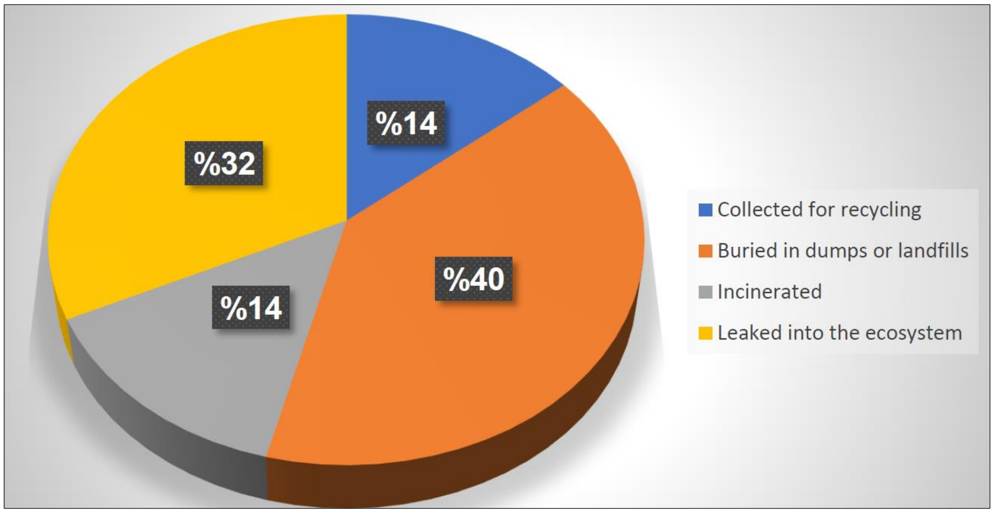


Figure 2: Average plastics waste status globally in terms of fate and transport (Ncube et al., 2021)

Plastics are produced 99% from crude oil and gas which are finite and limited natural resources obtained from refineries and petrochemical downstream industries. Worthy of mentioning is that 44.8% of plastics go into packaging as the dominant application followed by building and construction (PRI, 2020).

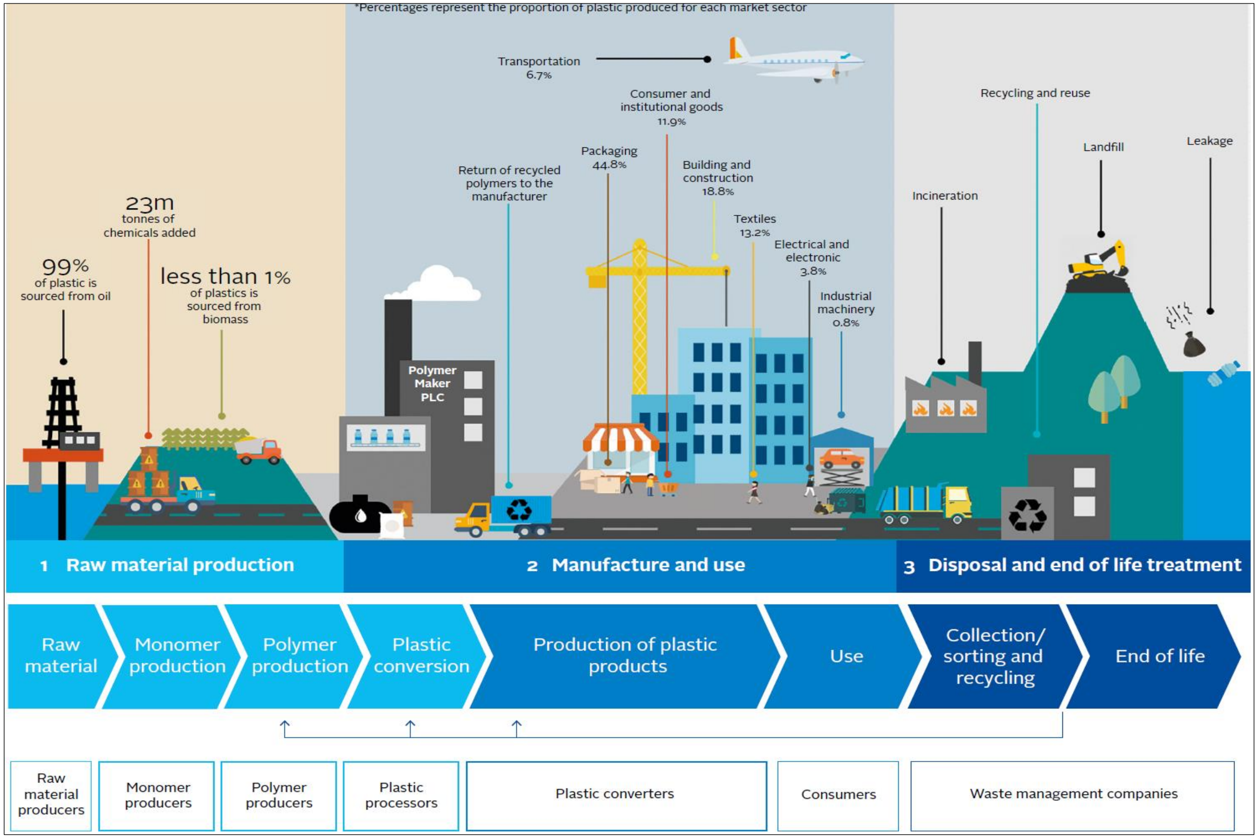


Figure 3: Lifecycle of Plastics and its holistic value chain (PRI, 2020)

2.2 Health, Safety and Environmental Impacts of Plastics Waste

Numerous academic articles have demonstrated the adverse and detrimental impacts of plastic waste on the terrestrial, aquatic and atmospheric ecosystems as plastics are classified as chemical hazards. They have serious repercussions and consequences for human health. On the terrestrial and aquatic ecosystem fronts, plastic waste directly leads to ecosystem pollution (Kumar et al., 2021). In addition, it leads to soil and water contamination negatively impacts the soil and ocean biodiversity and disrupts the food supply chain by inhibiting the nurturing of food crops growth. It leads to death once ingested and entangled by organisms, wildlife, marine and aquatic inhabitants, and livestock (Sharma et al., 2021). It has come to the forefront as a global menace threatening marine life and human health as plastics waste seep into our oceans and thus these microplastics are being consumed by the aquatic lives and damaging the food chain by its harmful effects on human health. This is since the process of making plastics entails the addition of huge quantities of toxic and harmful industrial chemicals that are proven to create toxic effects and dose-response to both humans and animals. These toxic effects emerge in the form of both local and systemic toxicities impacting locally (toxins affecting the eye, skin, respiratory systems through the various routes of entry for chemicals) and toxins that harm organ systems such as the liver or the kidneys (Visvanathan et al., 2021). The toxic industrial chemicals that constitute plastics have been reported to cause skin notation, sensitizer notation, irritant, dermatotic, poisonous, and carcinogenic notation with effects that are immediate and long-term (acute and chronic).

On the other hand, the irresponsible disposal of plastic waste has a detrimental impact on the atmospheric ecosystem. The toxic chemicals and hydrocarbons that form plastics once discarded into the environment followed by chemical release to the atmosphere, lead to climate change and air pollution. The impact inevitably could be observed with the Carbon Dioxide (CO_2) emissions, Particulate Matter (PM) and Greenhouse gases emissions leading to increased levels of Global warming and air contamination. Therefore, leading to adverse health and environmental consequences by further damaging the ecosystem due to the release of airborne toxic substances such as dioxin, a persistent organic pollutant in the environment, heavy metals, chlorine, hydrocarbons and free radicals (Zhang et al., 2020). Basel Convention "on the Control of Transboundary Movements of Hazardous Wastes and their disposal" classifies solid plastics waste in Annex IX List B3 as hazardous waste (B3 wastes containing principally organic constituents, which may contain metals and inorganic materials). Plastics are made of dangerous and hazardous industrial chemicals, for instance, Ethylene, Styrene, Propylene, Terephthalate, Acrylonitrile, Cyanide, Halogenated compounds, Peroxides, Sulfides, and many others (Aurisano et al., 2021).

Plastic wastes are unique and distinguished from the other types of Municipal Solid Wastes (MSW) such as paper, wood, food, etc. where plastics take up to decades, centuries and even millennia for them to decompose due to their chemical structure and strong chemical bonding. Plastic in landfills are still causing harmful impacts to the ecosystem as they take up massive areas of land, deplete the finite resources required to sustain life and damages biodiversity and add to ecological footprint. For a long time, plastic waste landfilling and dumping in empty spaces were the main approaches to discarding this type of waste. However, due to the substantial negative impact of implementing this approach, landfilling must be avoided. In fact, in many countries, this method has been banned (Majgaonkar et al., 2021). Landfilling of plastic wastes holds many drawbacks on all fronts, despite the feasibility and affordability. It is a major problem globally for many reasons. For example, in landfills, waste occupiesvaluable land spaces that can be benefited from. Moreover, due to the plastic's buoyant characteristic, it is forced to come to the surface, damaging caps and liners. Thus, creating a new issue of fire hazard due to their flammability and combustibility characteristics. Fire hazard is considered one of the serious concerns where the plastics can act as a fuel source to ignite and cause a fire that propagates rapidly, violently, and is difficult to extinguish (Robaina et al., 2020). The resultant smoke of the toxin chemicals and the particulate matter leads to air pollution, and resultant pollutants can pollute the nearby groundwater and soil consumed by living organisms. It has been reported by several studies that screened and surveyed oceanic lives and wildlife animals that many reported animal deaths have been found due to toxic contamination or ingestion of plastic waste. To summarize, plastic waste stockpiles contribute to spreading fire and pose a major serious threat to public health, safety, and the environment (Burgess et al., 2021).

2.3 Plastics Waste Management Hierarchy

The Waste Management approach is simply the collection of waste, transport, processing, and disposal. Specifically, the management of waste follows the waste management hierarchy displayed in Figure 4 wherein the handling strategies start off from the most preferred option of reducing, reusing, and recycling down the line to the least preferred option of landfilling (Neo et al., 2021). The source reduction and reuse phase are the processes of lowering the amount of waste produced by positive consumer cultures and behaviors (notably known as conscious consumerism). Instances of these are second-hand plastics utilization. Thus, it minimizes the generation of plastic wastes and extends the life of plastics. On the other hand, plastic wastecould be recycled mechanically or chemically generating numerous useful applications to be reused. Mechanical recycling yields products that can be utilized at home, garden decoration, outdoor play areas and backyards, plastics swings, flooring, furniture, sofa, etc. However, this route is often downcycling in nature producing inferior products (Reinales et al., 2020). Nevertheless, the chemical recycling route (such as pyrolysis) is one of the Best Available Techniques (BAT) that has beenadopted for decades and is very mature. It produces fuel oil from plastic wastes under a thermal degradation process in the absence of oxygen. It also produces synthetic gas, carbon black and char (Figure 5). All of which are attractive and competitive output products that can be used as feedstock recycling to reproduce plastics, and many other industrial refined products and essential building block chemicals such as Methanol and Hydrogen. It fully monetizes and maximizes the value of plastics waste and converts them into wealth. The products that could be generated from chemically recycled plastics are far superior and are often classified as upcycling. Therefore, this process route can repeatedly recycle the plastic wastes and extracts invaluable materials (Dubdub et al., 2020).

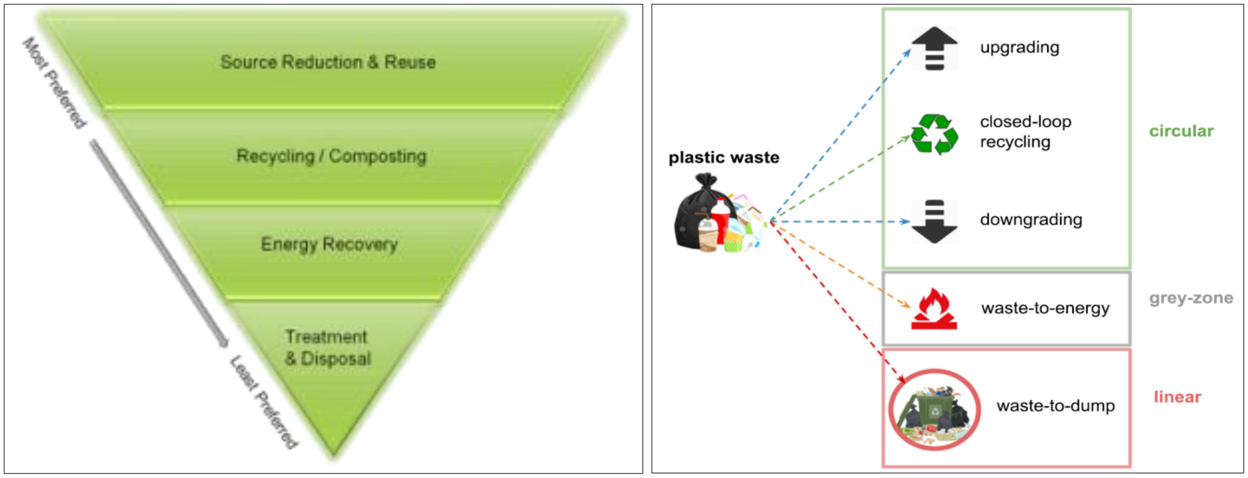


Figure 4: Waste Management Hierarchy and Pathways for Linear and Circular Economy Models (Neo et al., 2021)

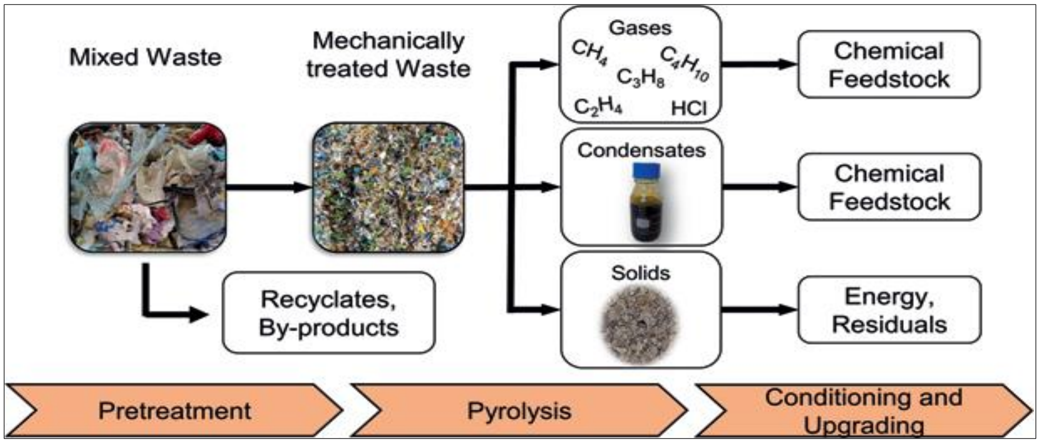


Figure 5: Valorization of Plastics Waste through Pyrolysis and Output Streams (Neo et al., 2021)

As per Merriam-Webster dictionary, pyrolysis is derived from the Greek word pyro meaning "fire" and “lysis” meaning separating. It was discovered by the inventor Jayme Navarro and is a chemical reaction process where organic materials in an oxygen-free medium are thermally decomposed and converted to materials of added value characterized by being recoverable and reusable. It is a thermal degradation process of organic material into smaller molecules that are also less complex. In addition, it is synonymously known as coking, carbonization, thermal depolymerization, destructive distillation, and thermal cracking. The pyrolysis process produces three main commercial and marketable products, pyrolytic gas, pyrolysis oil and char (mainly carbon black). The pyrolysis process occurs when the long-chain polymers are being heated in anaerobic conditions (absence of oxygen). This heating causes the organic molecules to vibrate and the higher the temperature the more rapid the vibration. Therefore, at elevated temperatures above 250℃,the weaker bonds in the molecules will be broken yielding new short-end molecules. These new shorter molecules will have lower molecular weights than the parent molecule which will be further broken down upon exposure to more temperature leaving the char residue. The main process parameters affecting the pyrolysis process and the quality and quantity of the pyrolytic products (oil, gas, and char) are the reactor temperature, reactor design and catalyst type (Majgaonkar et al., 2021).

2.4 The United Nations Sustainable Development Goals (UN SDG’s)

In 2015, the United Nations General Assembly has founded The Sustainable Development Goals (the Global Goals) which are a set of 17 interconnected global goals intended to accomplish a sustainable future for all United Nations members by 2030 (which the UAE is part of). Figure 6 below shows the UN SDG’s which as can be observed are very interlinked with the objectives and targets of waste management strategies on the environmental, social, and economic domains as exhibited in Figure 7 (UNEP, 2020). In addition, fulfilling the environmental pillars of the SDG’s necessitates the management of plastics waste and collectively addresses the ubiquitous plastics pollution which is dramatically having a negative impact on several lifeforms. Therefore, advancing and accelerating our progress towards achieving the UN SDG’s will inevitably have profound positive contributions on Clear Water and Sanitation (Goal 6), Climate Action (Goal 13), Life Below Water (Goal 14), and Life on Land (Goal 15). These are on the environmental front, however managing plastics waste will also have great positive impacts on the economic pillar by the positive economic returns from recycling in the form of profits, job creation, and increased GDP of the country due to industrial growth and economic diversification (Goal 8 and 9 Decent work and economic growth and industry, innovation, and infrastructure). Furthermore, on the social principal, having people’s awareness on this very significant challenge would also contribute to having a zero-waste model which would eventually lead to Quality Education (Goal 4), Sustainable Cities and Communities (Goal 11), and most importantly a key enabler would definitely be Goal 17 (Partnership for the Goals) (Meys et al., 2020).

Figure 6: UN SDG’s (UNEP, 2020)

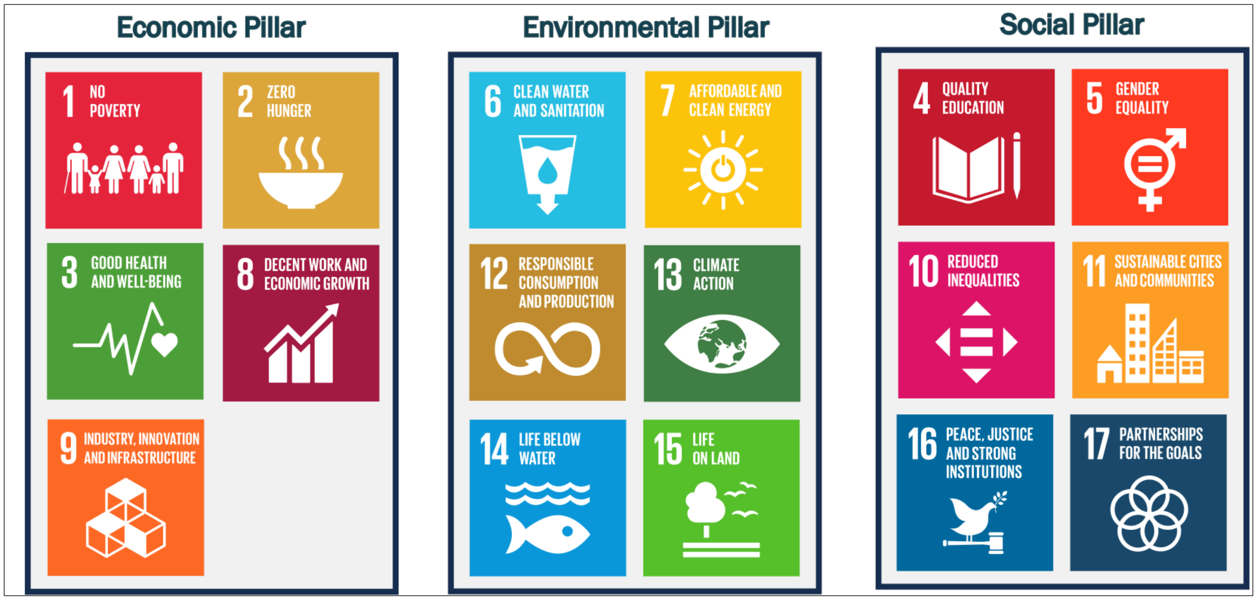


Figure 71: Categorization of the UN SDGs in relation to managing plastics waste (Meys et al., 2020)

2.5 Circular Economy

This section highlights how plastic waste management is in complete alignment and supports the circular economy strategies. Plastic waste management is a key enabler to a circular economy. The circular economy is completely different from a linear economy, as depicted in Figure 8. A linear economy is in operation worldwide since the first industrial revolution where the feedstock and raw materials flow out of the system, output products flow in for usage by consumers and eventually being discarded and disposed of, in the form of stockpiling and landfilling (Sardon et al., 2020). This linear economy has substantial damage to human health, the environment, and the economy. Plastics contain flammable materials that once burned will cause detrimental effects to the respiratory system of humans, pollute the air, contaminate water and soil. On the economy front, it leads to invaluable unrecovered crude and petroleum resources that are non-renewable.

Figure 8: Typical linear economy of plastics waste

In contrast, Circular economy has multi-faceted positive environmental and economic contributions to the society and all habitats. It offers a thriving business model which is by nature and design restorative and regenerative. It also promotes sustainability which is a sought-after strategy worldwide to maintain the value of the product, preserve material and energy resources from post-consumer products (Khoo et al., 2019). It prevents Climate Change and preserves the biodiversity in the ecosystem. In addition, it supports the zero-carbon initiative and lowers the Greenhouse Gas Emissions (GHG) that has been set by many countries and prominent energy companies worldwide by 2050 (the UAE is the 1st in the MENA region to set the Climate neutrality targets). Figure 9 below illustrates how plastics waste management supports indispensable industries and its linkage to supporting the growing strategies set for circular economy. Therefore, it will lead to fuel production that can be used in refineries and manufacturing industries and reusing the material which can be bolstered in the processes to produce better quality material than the virgin polymer (Bałazińska et al., 2020).

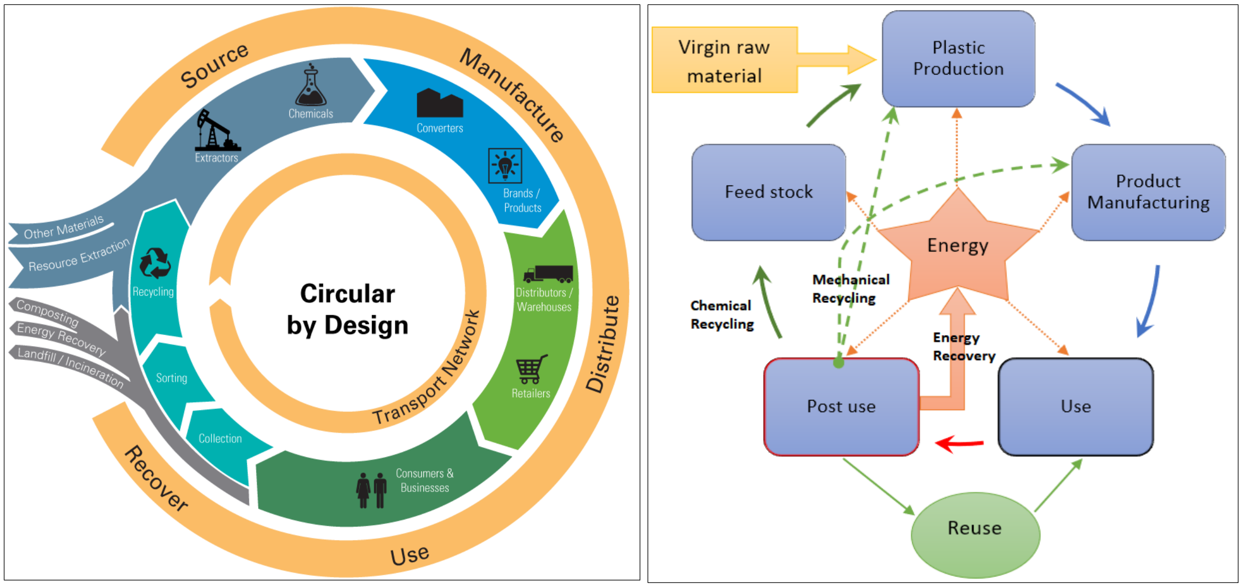


Figure 9: Plastics Waste Management Circular Economy odel

3. EXPERIENTIAL WORK

This section describes the systematic process conducted for the data acquisition and interpretation pertinent to the design project at hand. Multiple case studies have been performed in this study, the first case study focused on Abu Dhabi's practices and the others are case studies and success stories from EU countries. This will facilitate the activities for gap assessment, benchmarking, integration and solution development.

3.1 Abu Dhabi Case Study and Gap Assessment

In the 1st case study, observations and measurements were gathered to obtain knowledge and insights from the local government authorities from the Emirate of Abu Dhabi in reference to the current practices for managing plastic waste. The types of data collected are both quantitative and qualitative where graphical analysis and statistical methods are utilized to collect, store, and process the obtained information. In addition, the qualitative data will be analyzed by interpretations and categorizations. The results and analyses of the data will be elaborated on in this section.

A series of multiple engagements were conducted with key stakeholders who contribute to the plastics value chain to obtain both numerical and non-numerical data to explore the current methods being performed locally in Abu Dhabi. These engagements were in various forms such as archival research (existing manuscripts, database, and depositories), interviews, virtual meetings, focus groups, emails, and calls. The list below shows the interactions that were conducted with key stakeholders during the course of this design project and subsequently will detail the data obtained from these entities:

1. FCSC: UAE Federal Competitiveness & Statistics Centre
2. SCAD: Statistics Center - Abu Dhabi
3. MOCCAE: UAE Ministry of Climate Change and Environment
4. Tadweer: Abu Dhabi Waste Management Center
5. EAD: Environment Agency - Abu Dhabi
6. Khalifa University (KU)

As per EAD Policy number WMP EAD-EQ-PR-P-05 on "Waste Reuse, Recycling, Resource Recovery, Treatment and Disposal Policy": Plastic waste is defined and classified as Non-hazardous recyclable and non-putrescible solid waste. The percentage distribution of plastic waste from the total Municipal Solid Waste (MSW) accounts for 20.5% as per a recent survey conducted by EAD in 2019. EAD screened the use of plastic bags in the UAE and concluded that it is way higher than the global averages. Approximately in the UAE, every year 11 billion plastic bags are used with an average of 1,184 per person per year compared to 307 per person per year on the global average (EAD, 2020). Table 1 exhibits 2019 UAE statistics for the percentage (%) distribution of collected non-hazardous wastes by the method of treatment and disposing of. Figure 10 portrays Table 1 as a graphical representation of the results obtained from the UAE FCSC. It is to be noted that about 80% of UAE wastes are landfilled while only about 20% gets recycled in the UAE (FCSC, 2019).

Table 1: UAE FCSC non-hazardous waste data for 2019 quantities with % distribution of recycling and disposal methods

	Total	**Landfilling**	**Incineration without energy recovery**	**Incineration with Energy recovery**	**Composting**	**Recycling**
Quantity (Tons)	35,024,200	27,902,600	8,900	5,310	18,900	6,870,600
Percentage (%)	100	79.7	0.03	0.15	0.5	19.6

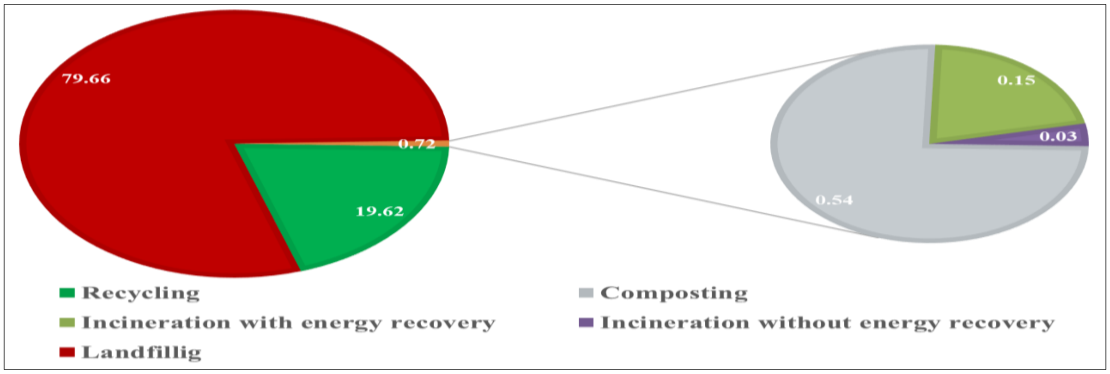


Figure 10: UAE FCSC non-hazardous waste data for 2019 with % distribution of recycling and disposal methods

Table 2 below shows Abu Dhabi-specific Municipal Solid Waste Data (MSW) for the collected and recycled MSW with the percentage (%) recycling for a period of 9 years of available data starting from 2012 up to 2020 (SCAD, 2020).

Table 2: Collected MSW quantities and recycled MSW with % recycling from 2012 up to 2020 for Abu Dhabi

Year	Collected Municipal Waste (Tons)	Recycled Municipal Waste (Tons)	Recycling Percentage (%)
2012	1,272,668	197,590	15.5
2013	1,528,093	244,495	16
2014	1,466,590	88,555	6
2015	1,678,983	329,470	19.6
2016	1,561,680	266,109	17
2017	1,372,140	268,302	19.6
2018	1,793,542	596,476	33.3
2019	1,927,065	421,557	21.9
2020	1,791,337	286,862	16
Average	**1,599,122**	**299,935**	**18**

Figures 11 and 12 present the graphical representation of Table 2 in terms of Abu Dhabi MSW collected and recycling quantities and the percentage (%) recycling of the MSW from 2012 to 2020 respectively. It is noticeable that Abu Dhabi's average landfilling rate is 82% while its average recycling rate is 18% which is low (SCAD, 2020).

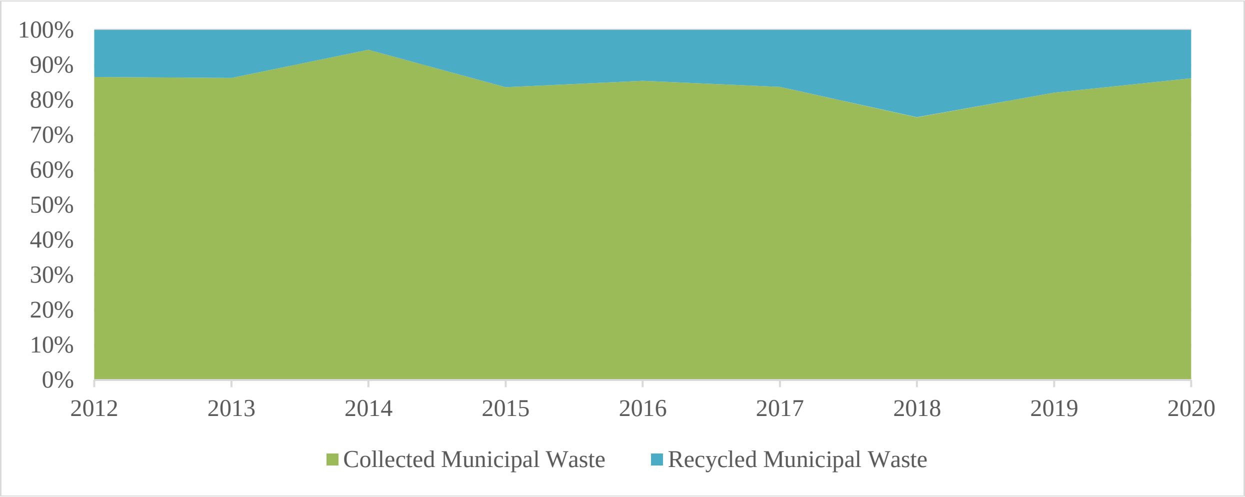


Figure 11: Abu Dhabi SCAD data for collected and recycled MSW (2012-2020)

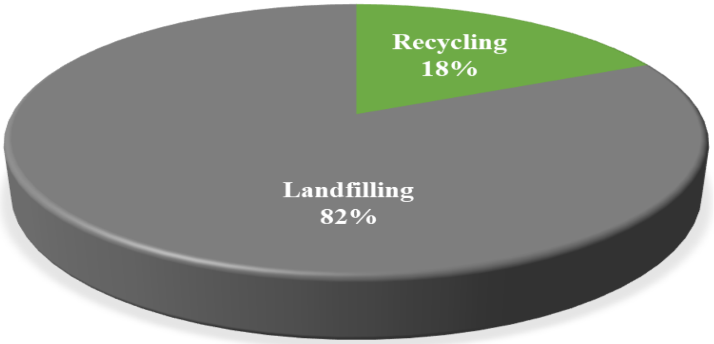


Figure 12: Percentage of Municipal Solid Waste Recycling in Abu Dhabi

Over the decades, Abu Dhabi is in continuous progress in the efforts of preserving the country's natural and finite resources. Abu Dhabi is handling its hazardous waste by developing recycling and recovery facilities and displacing landfilling by implementing recycling strategies. Abu Dhabi is currently mechanically recycling waste plastics by producing straps and pallets. Table 3 below summarizes the different plastics waste management practices adopted in Abu Dhabi. Tadweer currently operates only 1 plastics waste recycling facility, through the mechanical recycling route, where baling and sorting of the plastics waste quantities are performed and then converted into pallets and straps which is down-cycling in nature to keep the material in reuse. The plant design capacity is 16,500 Tons/year (Tadweer, 2020).

Table 3: Plastics waste management practices in Abu Dhabi

	Output Product (Purpose)	**Positive Impact/benefit**	**Negative Impact**	**Location**
Recycle plastic waste	Shredded plastics	- Reduce landfilling capacity - Used as input in other small applications - Positive impact on the environment	No serious negative impact however this method is down-cycling in nature	Al Ain
Landfilling	N.A.	N.A.	- Contamination of natural resources such as air, soil, surface, and groundwater. - Increases landfilling capacity - Imposes Fire hazards (leads to air pollution) - Metals and HC potential leaching	Al Dhafra

Table 4: Abu Dhabi plastics waste recycling facility

Facility	Plastics Waste Recycling
Location	Al Ain
Recycling Capacity	16,500 Tons/year
Products	- Straps - Pallets

These data demonstrate the fact that major transformative actions need to be put in place to transition from the current Plastics Linear Economy (Figure 8) to adopt a breakthrough model that promotes sustainability and Circular Plastics Economy. A summary of the major gaps identified in the current Abu Dhabi's practices is displayed in Figure 13 with 4 major categories; 1. Recycling facilities, 2. Linear plastics economy, 3. Consumer behavior and 4. Waste definition. The target is to address these deficiencies in the current system and optimize the current situation to reach a zero-waste model.

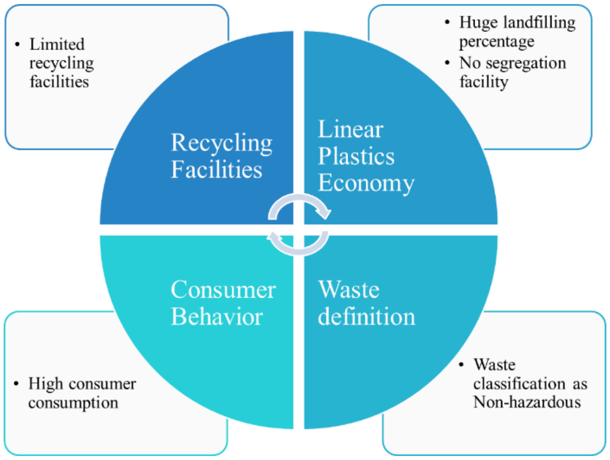


Figure 13: Percentage of Municipal Solid Waste Recycling in Abu Dhabi

3.2 EU Case Studies: Best Practices and Success Stories

A case study has been conducted on EU countries that are world leaders in plastics management through its full lifecycle. The study focused on the practices performed by the Netherlands, Germany, Italy, Spain and the EU recycling companies. In 2015, EU launched its 1st Plastics Circular Economy Action Plan which became an EU Directive 2018/851 and Legislative Framework on Plastics Circular Economy (EU, 2018). Figure 14 below exhibits the EU circular economy model starting from production, consumption, waste management to recycling (EU, 2018).

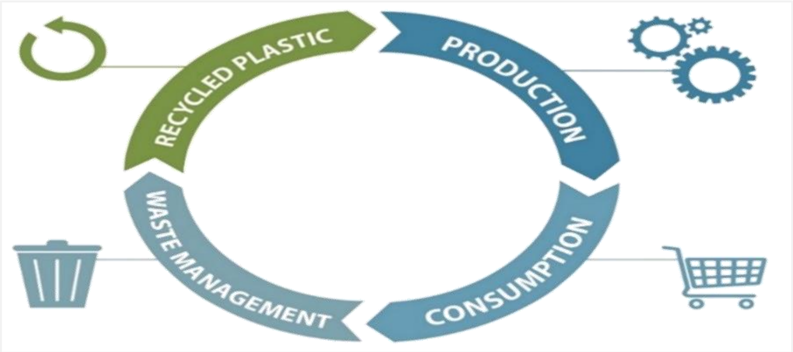


Figure 24: EU Circular Economy Model

Therefore, this has enabled various leading European Oil and Gas companies and recyclers to develop their plastics chemical recycling facilities in Europe. As a matter of fact, the plastics landfilling rates in the Netherlands and Germany are 0.4% and 0.6% respectively with both having 0% packaging landfilling rates (Plastics Europe, 2020). Moreover, plastics recycling (product resins from recycling plastics) go into various crucial applications as exhibited in Figures 15 and 16 where the major sectors are building and construction, packaging, agriculture and many others.

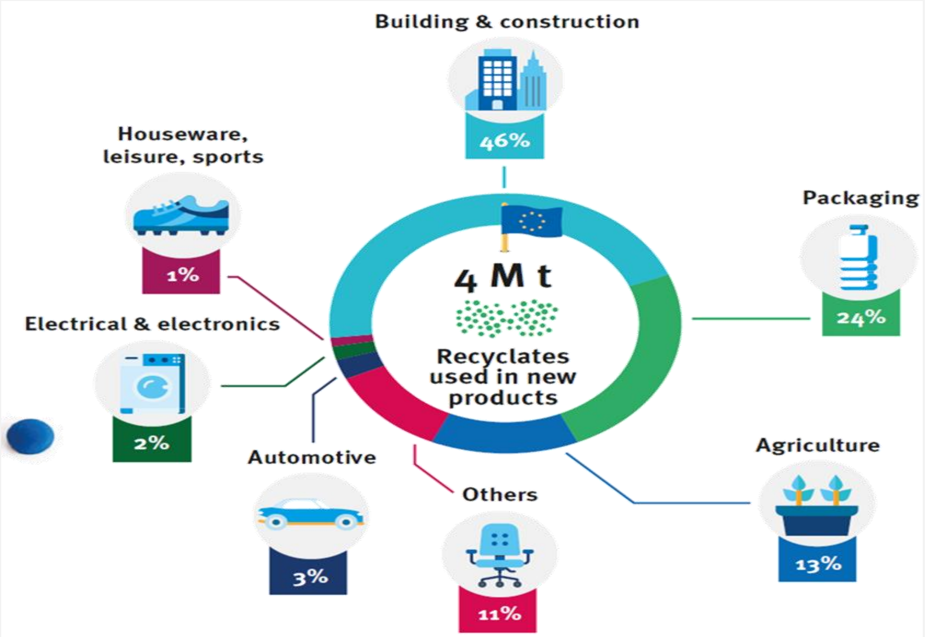


Figure 15: Plastics resin Distribution in Numerous Applications in EU

Figure 16: Example Plastics Recycling Applications in EU

For instance, Figure 17 shows the chemical recycling model that is being implemented by the Italian ENI Versalis, one of the world-leading Oil & Gas companies (ENI Versalis, 2021). In Spain, Plastics Energy, one of the world leaders, first mover and pioneer in chemical plastics recycling has commissioned in 2015 a plastics recycling chemical facility at an industrial and commercial scale which is at a world-scale capacity, as shown in Figure 18 (Plastics Energy, 2021).

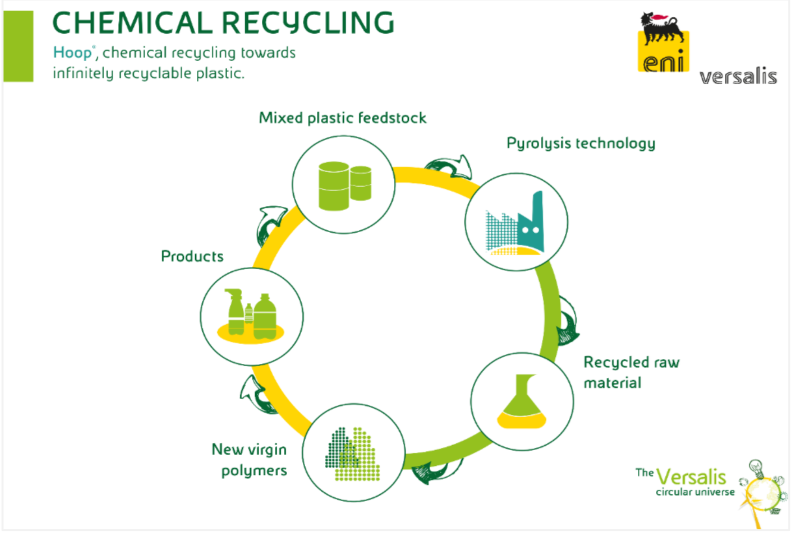


Figure 17: ENI Versalis Hoop Chemical recycling model based in Italy

Figure18: Plastics Energy Chemical recycling facility in Spain at an industrial scale

3.3 Benchmarking and Integration

Benchmarking against international best practices for the circular economy based on the EU model exhibited earlier in Figure 14 and the United Nations Environment Program (UNEP) Guidelines on Circular Economy, which was published in 2018, refer to Figure 19 below. The UNEP model aims for cleaner resources and production, lifespan extension, consumer role and behavior, collection, and recycling. Furthermore, an integration between the US EPA waste management hierarchy and OSHA risk management hierarchy has been implemented to devise a solution that looks at both aspects of these 2 hierarchies where we aim to introduce the elimination, substitution, engineering, and administrative controls to the waste management hierarchy. Therefore, this will eliminate completely the last 2 steps of energy recovery (incineration) and disposal (landfilling) stages. Consequently, synergizing the 2 hierarchies and benchmarking against the best practices from the legislative frameworks and guidelines.

Figure 19: UNEP Guidelines on Circular Economy

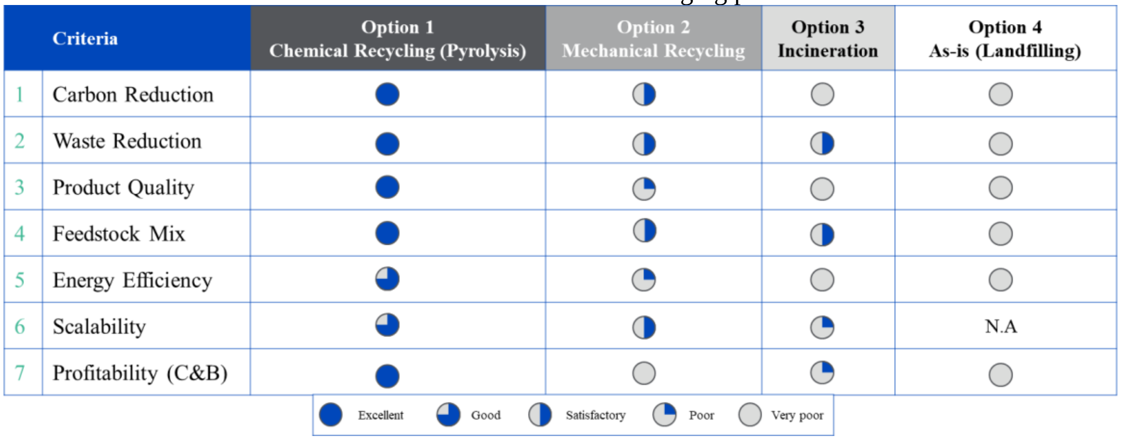
3.4 Results and Discussion (System Analysis)

A system analysis approach has been conducted which was a problem and goal-centered approach. The systems study was a top-down approach following 6 major phases; identified the major goal of having zero plastics waste (thus zero pollution) with defined criteria for evaluating multiple alternatives for managing plastics waste. The final step was auctioning and implementing the proposed solution in the form of a Framework and designing a computer simulation model using AnyLogic® computer software application. The simulation modeling followed 3 main stages; 1. Discrete event (process-centric modeling) then 2. Agent-based modeling and finally 3. Developed the System Dynamics model.

3.4.1 Alternatives Evaluation

An evaluation matrix has been developed to assess the 4 options for managing plastic waste (Chemical, Mechanical recycling, Incineration and Landfilling) based on 7 main criteria displayed in Table 5. Option 4 is the As-is situation being implemented in Abu Dhabi while the other options are to be explored and assessed for feasibility in Abu Dhabi. We can observe that and based on the literature review conducted that the most commercially viable approach is chemical recycling as it eliminates waste completely, it produces a product that is of the same product quality as the virgin polymer. It features feedstock flexibility accommodating all types of plastics and is scalable. The process of pyrolysis is energy-efficient not consuming huge energy compared to incineration or mechanical recycling options. The mechanical recycling process produces inferior products compared to the virgin polymer (downcycling) and cannot accommodate all types of plastic feedstock mix. Moreover, the incineration process is not environmentally benign as it produces a lot of carbon and GHG emissions that pollute our ecosystem. Also, the process generates a lot of by-product waste that needs to be disposed of (Ragaert et al., 2021).

Table 5: Alternative evaluation for managing plastics waste



	Criteria	Option 1 Chemical Recycling (Pyrolysis)	Option 2 Mechanical Recycling	Option 3 Incineration	Option 4 As-is (Landfilling)
1	Carbon Reduction	●	◑	○	○
2	Waste Reduction	●	◑	◑	○
3	Product Quality	●	◔	○	○
4	Feedstock Mix	●	◑	◑	○
5	Energy Efficiency	◕	◔	○	○
6	Scalability	◕	◑	◔	N.A
7	Profitability (C&B)	●	○	◔	○

● Excellent ◕ Good ◑ Satisfactory ◔ Poor ○ Very poor

3.4.2 Plastics Circular Economy Framework - The Blueprint

Figure 20 below displays the outcome of the proposed Circular Plastics Economy Framework (The Blueprint). It is based on remediating the gaps identified from the current practices in Abu Dhabi and the benchmarked EU case studies. This powerhouse is based on having governance for managing plastics waste fate and transport followed by strategizing and setting Key Performance Indicators (KPI's) to local entities to achieve the targets of 100% waste diversion away from landfills. The 4 main pillars set are to design circularity by developing biodegradable plastics and substituting them forother types of materials such as paper or wood whenever feasible. It also promotes Research & Development to explore other innovative solutions while producing plastics to design out and eliminate waste. Furthermore, the framework looks at consumer behavior to be changed to reduce, reuse sort, and donate their plastics products. It calls for collaboration across the entire plastics value chain and to build the infrastructure to manage end-of-life plastics. The house is underpinned by advanced recycling (also called Chemical recycling, pyrolysis, or feedstock recycling) which is an upcycling process competitive to virgin polymer. Moreover, community engagement, education and awareness are key strategies that are required to educate the people on plastics across their lifecycle and to conduct periodic clean-up campaigns on the beaches, deserts, parks, etc. focusing on the necessity of not littering plastics to our environment.

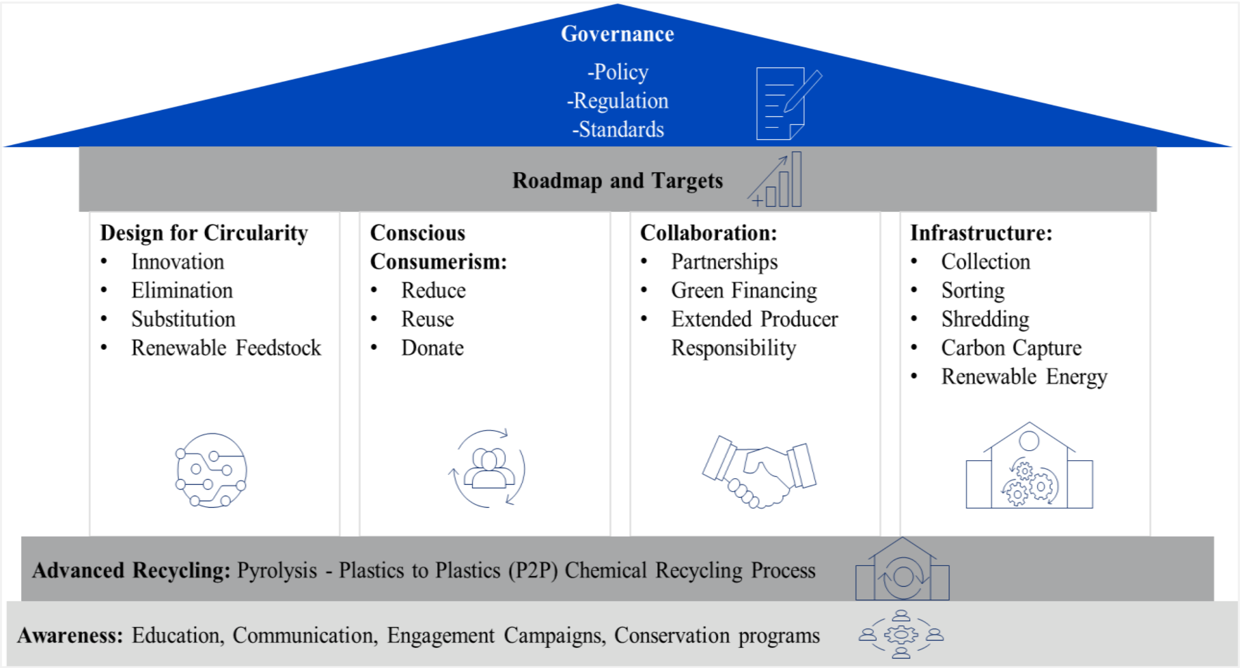


Figure 20: Framework and Blueprint for the Proposed Circular Plastics Economy

3.4.3 Model Design and Simulation

As a result of the evaluations discussed earlier in section 3.1 and the framework developed in 3.2, Option 1 for chemical recycling has been chosen due to its strengths in enabling a Plastic-to-Plastics solution and closing the loop to the circular economy. Figure 21 demonstrates the recommended closed-loop integrated Plastics Circular Economy Model starting off from fossil fuel extraction to steam cracker where the oil and gas are cracked to form the Olefins building blocks (Ethylene and Propylene) to Polymer production to produce (Polyethylene and Polypropylene) then polymer conversion for compounding applications followed by consumers (who need to reduce, reuse and donate) to material management of collection, sorting and shredding. Subsequently, the shredded plastics are entered into a chemical recycling facility to produce the pyrolysis oil that will repeat that fossil fuel route.

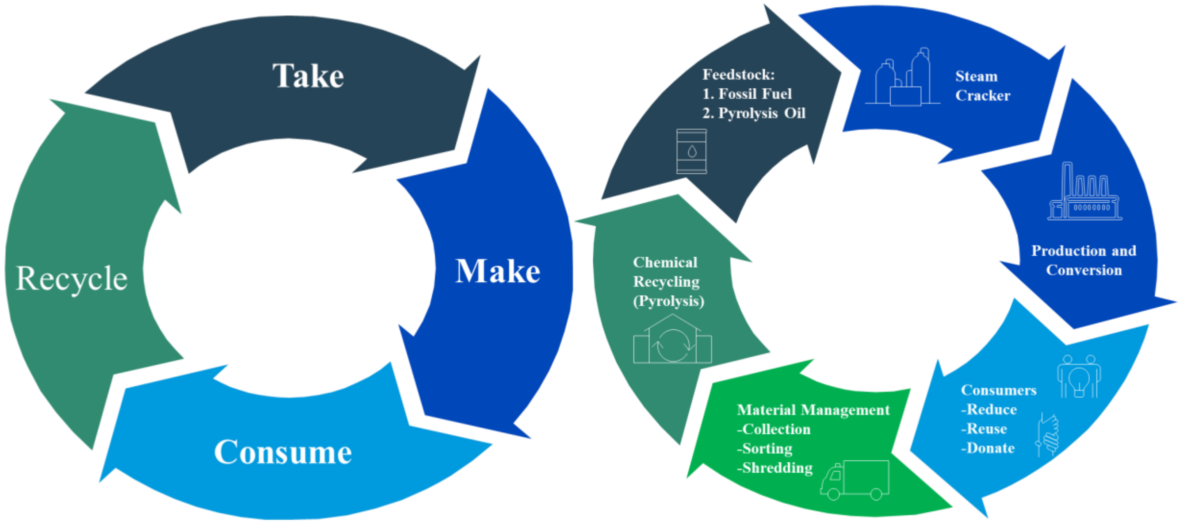


Figure 21: Circular Plastics economy proposed model

A Proof-of-Concept computer simulation model using AnyLogic® software application has been developed to simulate the recommended model in Figures 22 and 23. The simulation modeling followed 3 main stages; 1. Discrete event (process-centric modeling) then 2. Agent-based modeling and finally 3. System Dynamics model exhibited in Figure 22. Figure 23 demonstrates the same model; however, it highlights the key stakeholders in the value chain that will enable achieving such world-class solution through collaboration and cooperation creating synergies. For instance, Tadweer, ADNOC and EAD partner to realize this solution. Moreover, Khalifa University (KU) will play a central role in deployingits R&D capabilities to explore new innovative ways to produce biodegradable plastics utilizing renewable feedstock. KU could also support its capabilities in digitalization and artificial intelligence for autonomous sorting of MSW.

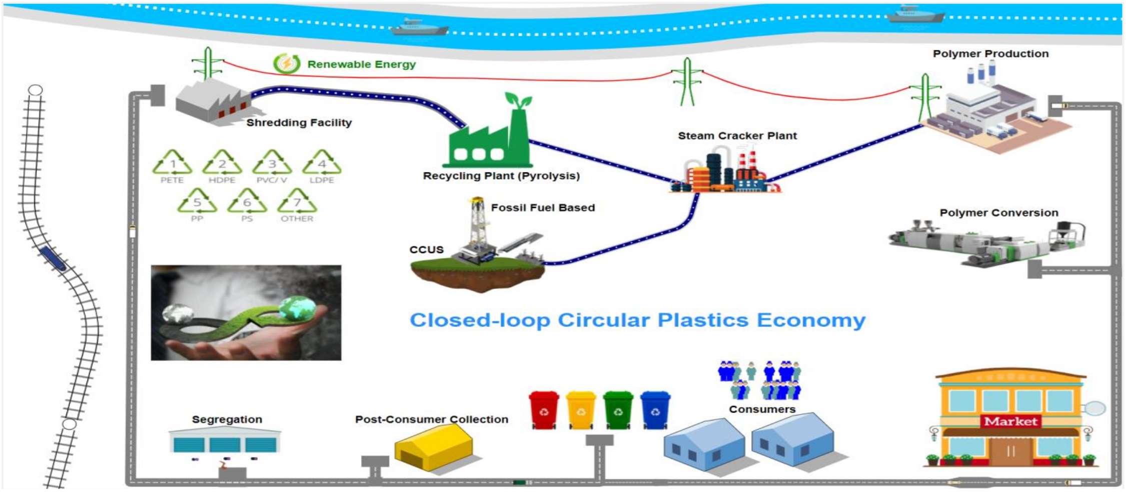


Figure 22: AnyLogic® simulation model for Circular Plastics Economy

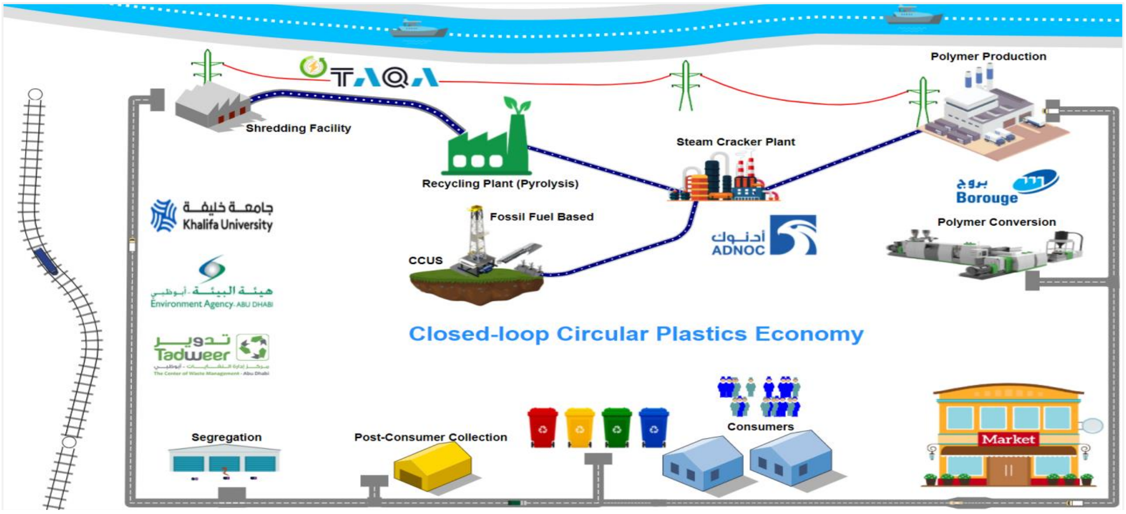


Figure 23: AnyLogic® simulation model for Circular Plastics Economy highlighting the key stakeholders

4. CONCLUSION

In conclusion, the study conducted a system analysis which was a problem and goal-centered approach for managing plastic waste in Abu Dhabi. It is therefore recommended to take stepwise actions for transitioning to a circular economy, starting with mechanical recycling, and gradually building up the chemical recycling critical mass. The systems study was a top-down approach following 6 major phases proposing a Circular Plastics Economy solution in the form of a Framework and designing a system dynamics computer simulation model using AnyLogic® computer software application. The recommended designed solutions to be adopted for the Emirate of Abu Dhabi are pragmatic, methodical, and integrated for managing plastic waste which is following the waste management and risk management hierarchies and benchmarked against the case studies conducted for EU where the best practices have been explored and analyzed. Furthermore, this capstone project studies plastic waste, drivers for managing it, regulatory framework, implications on the ecosystem, health and environment, and the current practices in the Emirate of Abu Dhabi. It also reviews prominent plastics waste recycling methods. Major gaps have been identified from the current practice being implemented in Abu Dhabi for the management of plastics waste. These observations were benchmarked with international best practices adopted in leading countries to propose actions that would bridge the gaps and suggest solutions. As per the gap assessment, the main gaps concluded for Abu Dhabi are limited recycling facilities, waste classification as non-hazardous, linear plastics economy, low recycling rate, no segregation and sorting facilities, and consumer behavior.

Plastic waste is a serious threat and challenge to our planet that must be collected and unitedly combated and addressed. Annually, global plastics production amounts to over 370 million tons per year with a small recycling percentage of only 14%. Moreover, the plastics production rate will inevitably continue to grow as the demand will keep increasing worldwide. The mismanagement of plastic waste is leading to land occupation through landfilling and stockpiling, fire risk, soil and water contamination, health issues to humans due to air emissions and many more. It is noticeable that plastic waste management will play an instrumental and impactful role in sustainability and promoting a circular economy. It reduces the carbon footprint impact and produces invaluable materials. It preserves the material through reducing, reusing, and recycling routes. Implementing the Circular Economy principles of Circulate Products and Materials, Eliminate Waste and Pollution, and Regenerate Nature will certainly have a positive impact on our ecosystem enabling the achievements of UAE’s environmental protection, Sustainable Development Goals, UAE Net Zero by 2050 Strategic Initiative and the Paris Accord for Climate Change.

The next steps of this study are targeted to engage with the relevant stakeholders in the plastics value chain and share with them the outcomes of this study and the significance of adopting a circular economy model for managing plastics waste showcasing its substantial benefits to the environment, society, and the economy. The Ministry of Education is a great candidate to extend their support to educate the students on this critical challenge and ways to curb it by encouraging positive behaviors in the community, guiding them on sorting their plastics waste and the need to reduce consumption and reuse and donate our plastic products. Circular Economy principles can be applied to other types of Waste and Municipal Solid Waste such as food, paper, wood, etc. where it is aimed to explore the results of applying such principles similar to plastics. The main outcome of the research is writtenin this section. The author must mention the conclusion of the research in brief. The limitations and the future work of the research can also be mentioned here.

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