ENVIRONMETAL SUSTAINABILITY ASSESSMENT OF RECYCLED PET BOTTLES USING LIFE CYCLE ASSESSMENT APPROACH

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ISLAMABAD, PAKISTAN
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This work is submitted as a dissertation in partial fulfilment for the award of the degree of Master of Philosophy in Environmental Sciences

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To my parents for their faith, endless love support and encouragement

<u>DECLARATION</u>

I, **"Farman Ullah" (Registration No. 02312111003)** hereby declare that my M.Phil. thesis titled as **"Environmental sustainability assessment of recycled PET bottles using life cycle assessment approach"** is all my own effort done in Environmental Biology and Ecotoxicology Laboratory, Department of Environmental Sciences, Quaid-i-Azam University, Islamabad. All the investigations, findings, results, conclusions of this research have neither been previously presented anywhere nor published in any local or international forum.

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Dated: ___________

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It is to certify that the research work presented in this thesis, titled "**Environmental sustainability assessment of recycled PET bottles using life cycle assessment approach"** was conducted by **Mr. Farman Ullah (Registration No. 02312111003),** under the supervision of **Prof. Dr. Riffat Naseem Malik (T.I).** No part of this thesis has been submitted elsewhere for any other degree. This thesis is submitted to the Department of Environmental Sciences, in partial fulfillment of the requirements for the degree of **Master of Philosophy** in the field of Environmental Science, Department of Environmental Sciences, Quaid-i-Azam University, Islamabad, Pakistan.

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ABSTRACT

In this study, life cycle assessment was applied to assess the environmental impact of polyethylene terephthalate (PET) bottle-to-fibre recycling. The following scenario, based on our field survey, was evaluated. The functional unit was one metric ton of recycled polyester staple fibre. The system boundary ranged from cradle-to-factory gate. All the inventory data of recycling processes were obtained from field visits, observations, and semi-structured interviews with the recyclers. The LCA results showed the numerical value of global warming potential (701 kg CO2 eq), acidification (3.32 kg SO2 eq), eutrophication (1.82 kg PO4- eq,) abiotic depletion (7.97 kg Sb eq), ozone layer depletion (7.62E-05 kg CFC-11 eq) human toxicity (762 kg 1,4 DB eq) fresh water ecotoxicity (429 kg 1,4-DB eq) and marine ecotoxicity (705754 kg 1,4 -DB eq) of recycling of 1 ton of PET bottles into fibre. Conventional electricity consumption showed an average of 49% higher impact in seven out of ten impact categories, As compared to virgin PET fibre production, the recycled PET fibre had much lower environmental impact (below 20%) in eight out of ten impact categories except eutrophication and freshwater aquatic ecotoxicity (66% to 86%) respectively.

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FARMAN ULLAH

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CHAPTER 1

INTRODUCTION

1. Introduction

Plastics play an important role in our daily life. Plastics are organic polymers of large molecular mass. They are commonly derived from petroleum. There are two main categories of plastics, thermoplastics, and thermosetting plastics. Thermosetting plastics cannot be melted on heating (Bakelite) while thermoplastics can be recycled on heating (PlasticsEurope2022). One of the most significant thermoplastics, sometimes known as "polyester" in the textile industry, is polyethylene terephthalate (PET). In 1940, Winfield and James. Dickson invented the first PET plastic in England while conducting a phthalic acid test. PET fiber production did not start until 1954. In the meantime, DuPont had independently developed a useful terephthalic acid preparation method by 1945, and the company started making Dacron fiber in 1953. PET quickly became the most useful fiber among synthetic fiber. Advanced molding technology was developed in the 1970s, enabling PET to be transformed into long-lasting, crystal-clear beverage packaging bottles. Terephthalic acid (TPA) and ethylene glycol (EG) are polymerized by heating under the presence of catalysts to produce PET, a molten substance which is converted into fibers or hardened into plastic bottles (Suhaimi et al., 2022). Over 50% of the global market for synthetic fibers is dominated by PET fiber. PET film was developed in the 1950s and was initially used for X-rays, photography, and cassette recording. Approximately 80% of the global total thermoplastic polymers produced are constituted by PET, polyethylene (PE) and polypropylene (PP)(Leng et al., 2018). PET is spun into fibers for textile fabric and molded into single use beverage packaging bottles. Most of the world's PET production was converted into polyester fibers (65%), bottles (30%), and other materials (6.2%). It is feasible to efficiently produce fabrics from recycled post-consumer PET bottles, which may ultimately be designed to produce items like shirts, bed sheets, and pillows (Park & Kim, 2014). The improvements in the PET manufacturing process led to a wide range of industrial uses, which raised consumer demand for PET and led to the production of PET by several multinational firms under various trade names. The demand for PET bottles has significantly increased since 1974, when the first plastic bottle was introduced. The increasing trend in shortage of freshwater resources, improved living standards, and the special qualities of PET bottles, might be the reason for the sudden rise in demand for PET bottles. Every minute, one million plastic bottles are sold globally (Wang & Salmon, 2022). About 28 million tons of PET beverage bottles were consumed globally in 2018. Around 8300 million metric tons of plastic have been produced over the past 65 years, and 79% of this is lying in landfills (Ügdüler et al., 2020). Studies show that approximately 63 percent of the textile fibers are derived from petrochemical fossil whereas cotton, the most popular natural fiber, contributes only about 24 percent of the fiber production (Sandin & Peters, 2018). However, due to the large amount of waste left in ecosystems because of the growing production and consumption of PET bottles, the environment and human health have suffered badly. The waste production is strongly correlated with its economy of the country and as its income goes up, so does the percentage of plastic waste in this overall waste (World Bank Group, 2018).

PET plastic is generated using petroleum and it does not biodegrade or photo degrade rapidly (approximately 1-3% in 100 years), it poses a significant environmental threat which leads to a significant increase in waste at already overloaded landfills (Arena et al., 2003). Although PET plastic provides no direct damage to the environment after manufacture, it contributes significantly to the waste accumulation in landfills, clogs sewage systems, and serves as a breeding ground for a variety of parasites (Foolmaun & Ramjeeawon, 2013). To counter these problems, various advanced technologies have been invented to recycle the waste, so contributing to the solution of the issue. In this regard, the fundamental advantage of PET plastic is its capacity to be continuously recycled, either in a closed loop or open loop recycling system leading to reduce waste and conserve natural resources. Littered used PET bottles in the environment lead to a negative impact on the natural environment (water, soil, and air). The impact on human health of non-biodegradable plastics and the chemicals and raw materials added during plastic production process have been studied in recent years (Pjanic et al. 2017). "The most abundant recycled plastic is PET, commonly, PET bottles and containers are recycled and spun into fibers for carpeting or fiberfill. When PET bottles collected in clean and pure form may be recycled into its original applications and procedure has been developed for chemically dissolving the polymer into its precursors for reproducing into the PET. The European Union has established a Resin Identification Code (RIC) to identify the type of plastic polymer it is made of and to ensure the plastic waste treatment and recycling. RIC is a numerical sequence from 1-7 and a series of acronyms. PET plastic bottles have RIC-1 which means that it is 100% recyclable.

According to the World Commission on Environment and Development (WCED), a sustainable development depends on the earth's life support systems to allow the present generation to use the natural resources without compromising on the next generations to be able to meet their needs. Consequently, sustainable development relies on environmental health. Hence LCA is a quantitative scientific tool which is used to analyze the sustainability of any activities, services, or products.

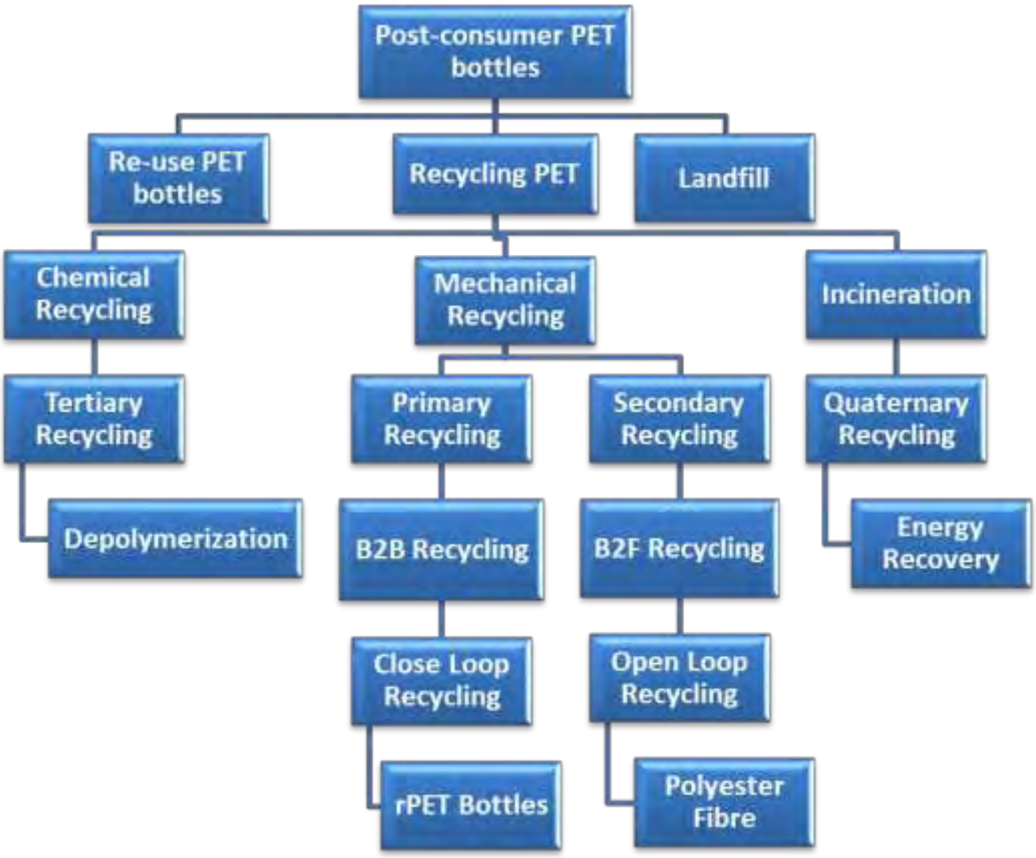


Figure : 1.1 PET bottles recycling strategies and technologies

1.1 Global status of PET bottles recycling

PET bottles account for 67 percent of the market share in the beverage sector among mineral drinking water packaging, carbonated beverages, energy drinks, tea, and coffee, according to data retrieved from Euromonitor (London, UK). In the United States in 2021, 44.7 percent single use PET bottles less than one liter beverage packaging bottles were used. According to the USA Environmental Protection Agency (US-EPA), in 2018, 35.7 million tons of plastic waste, or 12.2% of all municipal waste, were produced in the United States. This plastic waste also comprised HDPE and polyester packs, wraps, bottles, and jars along with the PET bottle waste and 27 million tons of plastic waste was landfilled, or 18.5% of all solid waste. The amount of recycled plastic packaging was only 4.5%. Data from the European Economic Area for the European Union showed that an average of 34.4 kgs of plastic packaging waste was produced per European Union citizen in 2019. The average amount of waste recycled per person was 41% (14.1 kg).

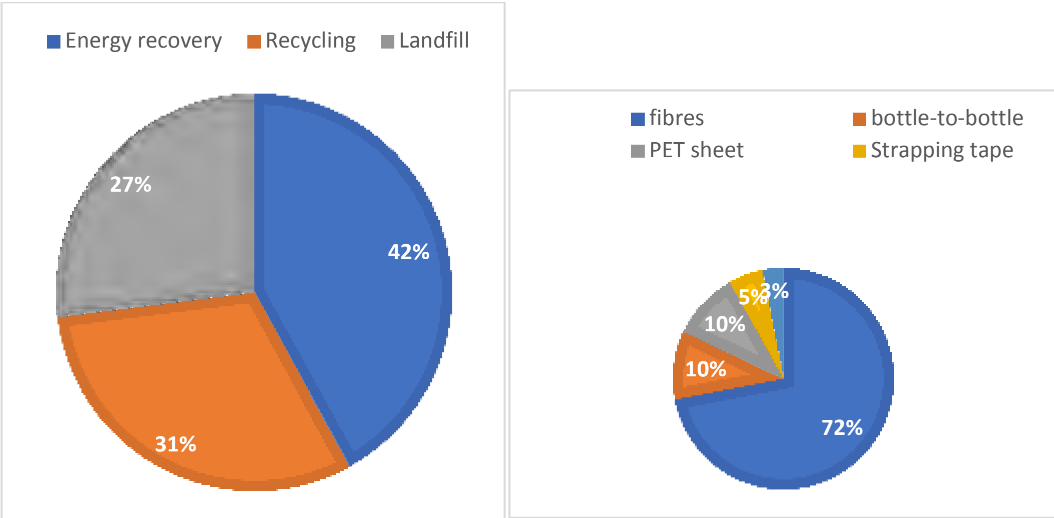


Figure : 1.2 Management and application of recycled PET waste in Europe (2016)

Source: EU's Environment Commission

Around the world, PET waste represents 12 % of all solid garbage. Pathways have been developed by the EU's Environment Commission so that member countries may drastically cut back on plastic waste leakage. These strategies include ideas for encouraging a shift in consumer behavior, enhancing waste management through waste collection, waste sorting, and recycling, along with limiting the types of waste that may be dumped in landfills (Benyathiar et al., 2022). Only around 9% of the projected 6.3 billion tons of plastic waste produced worldwide to date has been recycled. The remaining 79% has been poured into the environment, with another 12% being burned. Eighty percent of marine litter is made up of plastic debris, and 4.8 to 12.7 million metric tons of plastic are shown to be dumped into the oceans annually. Over 84% of water quality tests worldwide include micro-plastics in them. Products abandoned after one year or fewer of usage account for almost 40% of trash. For most plastics, recycling is an option worth considering, although it is still in its initial stage. PET is an exception and has a higher recycling rate (Hira et al., 2022).

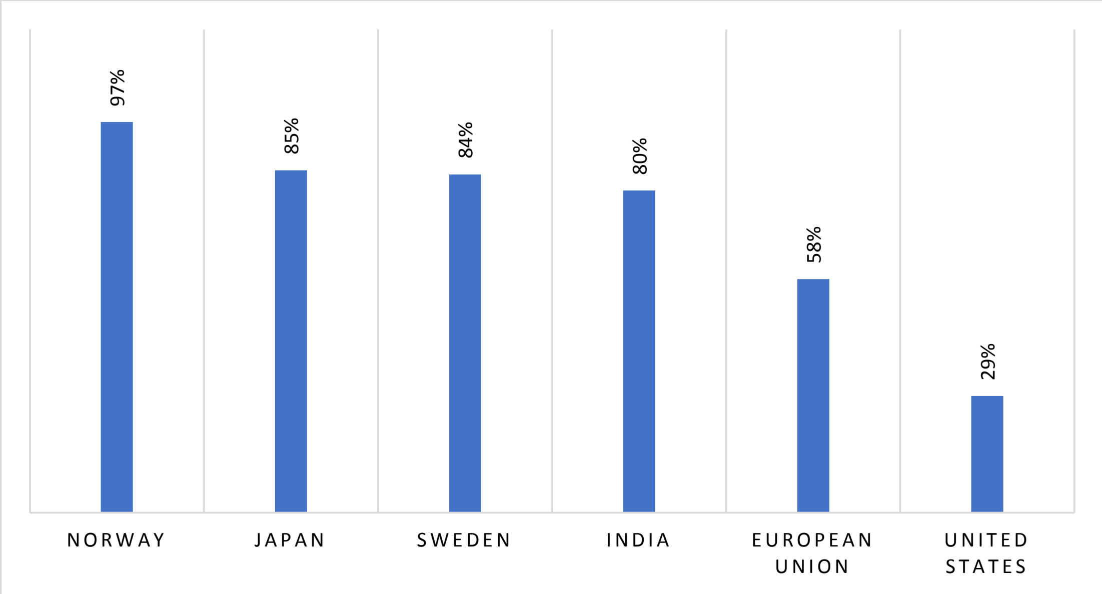


Figure : 1.3 PET bottles recycling rate (2018)

Source: Statista2023

In 2018, Norway has the highest recycling rate in the world for Polyester (PET) plastic bottles, at 97%. In contrast, just 29% of these bottles and cans were recycled in the United States. Norway's effective deposit return system is one of the reasons for the country's high recycling rate. There is a little surcharge added to the price of the beverages for plastic bottles, however once the bottles are returned to reversed vending machines, the surcharge is refunded to the buyer. Seeing the achievement of the plan, other countries have adopted similar initiatives. Eighty-six percent of the United Kingdom citizens agreed that supermarkets should participate in deposit return programs for plastic, glass, and aluminum beverage containers (Statista 2023).

1.2 Plastic waste management and recycling in China

An approximately, 50% of imported plastic waste in China were made up of PET. In China over the past 20 years, there have been 78 million tons (Mt) of PET bottles recycled (2000-2018). 29 Mt of waste PET bottles, which made up 37% of the total recycling, were among them and represented 40% of global exports. The majority of used plastic packaging in China were open-loop recycled or down-cycled to create PET fibers which greatly increased PET circularity globally, decreased the need for virgin PET content, and prevented the use of 233 Mt of CO_2 equivalent and 109 Mt of oil-equivalent fossil fuels. Due to the burdens placed on the natural environment and public health by the plastic waste treatment, the Chinese government prohibited further import of plastic wastes in 2018. Recycling used PET bottles, however, also reduces the need to produce new PET bottles and their associated harmful emissions, including the usage of fossil fuels and un-quantified greenhouse gas emissions (Ma et al., 2020). Since the start of the 21st century, China has been the largest post-consumer plastics importer in the world. In 2018, the Chinese government's announcement of import ban on all post-consumer plastics had a huge impact on how post-consumer plastics flowed globally. This plastic garbage import restriction was implemented to save the environment and public health in China (Ma et al., 2020). In 2016, 53 percent of the total world collected post-consumer PET bottles was treated in China, and an estimated 30% of the China 's total polyester fiber demand was fulfilled from recycled PET bottles (Aizenshtein, 2016). In China, there were 78 million tons (Mt) of PET bottles manufactured between 2000 and 2018, which is the equivalent of 7 tons of discarded PET bottles produced per minute. About 49 million tons (63%) of such used bottles came from domestic production, while 29 Mt (37%) came from the other countries. Interestingly, China was a major importer of discarded PET bottles before 2018. The quantity of discarded PET bottles imported into China was 290 times more than the amount exported. PET bottle waste recycling capacity in China was five times higher than that of the domestic output, showing that the excess recycling capability much exceeds the quantity domestically generated (Ma et al., 2020). Out of the total 78 million tons of post-consumer PET bottles, approximately 90% were recycled in China. Post-consumer PET bottles are mostly utilized to make recycled fiber goods, which are then converted into clothing in China. This process is known as open-loop recycling. However, just 5% of China's recycling technology uses the most advanced sustainable recycling technology for bottle-to-bottle (BTB) recycling, in accordance with a China National Resources Recycling Association (CRRA) research. Because in China Bottle-To-Bottle recycling technology is still comparatively outdated and the safety of recycled bottles for beverages cannot be assured, these recycling bottles are utilized to produce "nonfood contact grade" bottles for fertilizer and pesticide packaging. The proportion of surplus import recycling dropped sharply in 2018 following China's enforcement of its restriction on all types of waste plastic goods import (Ma et al., 2020) .

Figure : 1.4 Imports and recycling of PET bottles waste in China

Source: Ma et al., (2020)

China has been the world's top manufacturer of the polyester. Over 55% of the world's polyester production capacity is in China, and the country's polyester self-sufficiency rate is 100%. As a result, 52 Mt of PET bottles were produced in China over a 19-year period. Fortunately, China's strong record of plastic recycling can contribute to the conservation of natural resources. (Petrochemicals). In China, 90% of PET bottle waste was converted into recycled Polyester fibers, which has been used to make fabrics. Due to China's substantial PET bottle recycling program, virgin PET fiber and polyester were therefore not needed, which notably, China was pushed to become a major exporter of upstream items due to a serious over capacity problem in its polyester manufacturing. Between 2000 and 2018, their export amounts have increased at yearly rates of 45% and 21%, respectively saving the consumption of two- minerals (oil and coal)(Zhang et al., 2020). Recycling one kilogram of PET plastic may prevent 3.2 kg of CO_2 equivalent emissions and save around 1.5 kgs fossil fuels. Due to the avoidance of the production of virgin PET in China over the course of the 19 years, approximately 109 Mt oil-eq and 233 Mt CO_2 eq were saved, and 37% of recycled post-consumer PET bottles were imported from abroad, saving 40 Mt oil-eq of fossil fuels and reducing 85 Mt CO_2-eq emissions from the recycling of the imported PET bottles. Additionally, recycling prevents the requirement for extra fossil resources extraction for the manufacturing of virgin PET bottles (Ma et al., 2020).

1.3 Plastic waste management in Pakistan

Since Pakistan relies on just one kind of old conventional waste disposal method – landfilling. Pakistan's waste management system may be deemed antiquated. Moreover, it utilizes municipally maintained infrastructure and often outdated or inadequate equipment. The recycling sector is among the few in which private actors are actively involved, although their presence is limited, and their activities are poorly controlled. As a result, waste collection, processing, and dumping have become a primary issue at the national level. In the mid-1980s, PET bottles were first used in Pakistan, when multinational beverage companies expanded their manufacturing line to South Asia. In a few years, more PET bottles were produced. industries started to emerge. Currently, Pakistan produces 70% of its own PET resin, with the remaining 30% coming from imports. The two largest PET producers, Gatron and Novatex, produce approximately 345,000 Mt of PET resin annually and distribute it nearly evenly between the domestic and international markets. The companies employ this PET resin to make 2.5 billion preforms annually that are uniform and reliable and are then molded into PET bottles. These PET bottles are sent to large distributors like Coca-Cola, PepsiCo, Nestle, etc. The domestic market in Pakistan is currently Southeast Asia's second largest market after India, with the bottling industry growing at an average annual rate of 15%(Floor, 2016) According to surveys undertaken by WWF-Pakistan, plastic accounts for about 65 % of the waste that winds up on seashore. PET bottles, lids, plastic containers, balloons, packages, shoes, broken equipment, cast-off fish traps, and plastic bags make up the waste.(Scoping Study for Pak Waste Wwf 2020) . Pakistan lacks an effective waste management system, like other emerging nations, which causes plastics to be inappropriately discarded of or treated after use, contributing to serious environmental problems. Post-consumer PET bottles left behind with other waste after usage may later be separated by waste pickers and junk dealers. The health and welfare of the public are at risk since most of the municipal waste is openly burned, dumped, or buried in unused spaces. According to the ministry of climate change, major urban areas in Pakistan produce 77,000 metric tons of solid waste per day. Pakistan largest city, Karachi, produces more than 13,000 metric tons of municipal solid waste per day. Urban solid waste management is a big issue in all big cities of Pakistan and the fundamental failure include administrative roadblocks, a lack of urban planning, insufficient waste management tools, and a lack of public awareness. Ineffective infrastructure management causes plastic contamination in landfills and water sources. Pakistan's Indus River, which carries more than 164,332 metric tons of plastic waste, is the second-most plastic-polluted river in the world.(*Ministry of Climate Change Policy and Action on Waste and Plastics in Pakistan Background: SWITCH-Asia*, 2021)

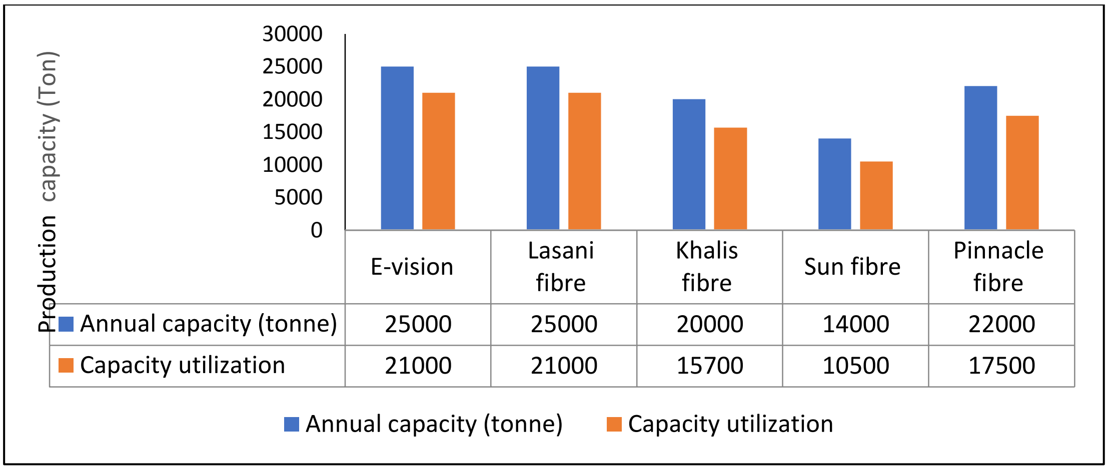


Figure : 1.5 Installed capacity of recycled polyester staple fiber in Pakistan

Source: Bloomberg, Ibrahim Fibres, Federal Board of Revenue

Urbanization is increasing over the whole of South Asia. As a result of human increasing population, urbanization, industrialization, and changes in consumer habits, both the amount of solid waste produced and the type of materials that compose that waste are on the rise (Gomes et al., 2019). Local community size, demography, and socioeconomic condition, as well as the average income, all influence the quantity of waste produced. Recycling trends demonstrate that wasted plastic from packaging streams, such as PET bottles, is one of the major drivers of the plastic recycling industry. Plastics ultimately deteriorate and pollute our land and water since they have a limited useful life. A significant contribution to plastic pollution is the lack of baseline data on the types of plastics manufactured, retrieved, and recycled in Pakistan. In formulating its recommendations for waste management, the Pakistan Environmental Protection Agency (PEPA) determined that plastic constitutes a substantial component of the country's solid waste. In Islamabad and other cities, small businesses and the informal sector have created strong recycling, reuse, and repair infrastructures, achieving cost effective recycling and recovery rates. Twenty to thirty percent of the waste collected door-to-door is recyclable. The marketing chain illustrates that each retailer employs a fixed number of hawkers to collect and resell left over goods (Bigas et al., 2013). In recent years, Pakistan's solid waste management (SWM) concerns have received a great deal of attention, mostly due to the country's increasing environmental fragility. Recent evaluations indicate that waste production rates in Pakistan's largest cities vary from 0.283 kg to 0.613 kg per person per day, with annual growth rates ranging from 3.67% to 7.42%. Pakistan has the lowest ranking in South Asia for effective plastic disposal. Out of 30 million tons of Pakistan's annual solid waste, 9% is composed of plastics, with an approximate 0.2 million tons of plastic debris flowing down the Indus River and into the Arabian Sea. Approximately 55 billion plastic bags are produced yearly, most of which are disposed of in landfills and rivers. This is a serious issue for wastewater treatment facilities. In Pakistan, municipal waste management and the disposal of plastics are uncommon concepts. Local governments need an adequate waste management system. According to latest projections, Pakistan's Municipal Solid Waste (MSW) generation is 50,438 tons each day, or 0.84 kg per person per day. It could reach 1.05 kg per person per day by 2025. 18% of municipal solid waste is plastic, 5% is cardboard, and 67% is organic. Compared to countries with a comparable population and income, this rate of plastic waste is unusually high. The surprisingly large volume of plastic garbage in Pakistan's municipal solid waste poses a significant problem for the nation. If Pakistan's existing plastic waste management policies are inadequate and ineffective, negative future results may occur. Transporting plastic waste outside the city is not a financially feasible solution for Pakistan because of the less availability of land in urban areas and the increasing cost of transportation and incineration of waste renders waste excessively wet and demands expensive preparation. It is also economically unfeasible to biodegrade it. Therefore, reusing and recycling of plastic waste in Pakistan is the most viable option for plastic waste management(Ali et al., 2021). Pakistan's annual plastic waste production is projected to increase from an anticipated 3.9 million tons in 2020 to an average 6.12 million tonnes in 2050, because of an increase in plastic product use. Almost 70% of the massive amount of plastic waste gets discarded in landfills, mismanaged dumps, or is dispersed over both land and water, clogging drains, and destroying fertile soil. Currently, only 33% of Pakistan's waste can be recycled because of a lack of infrastructure and resources. The Ministry of Climate Change and the Pakistan Collect and Recycle (CoRe) alliance gathered environmental experts, lawmakers, and companies to establish sustainable solution for collecting and disposing of plastic waste in Pakistan (*Ministry of Climate Change Policy and Action on Waste and Plastics in Pakistan (*2021).

1.4 Life Cycle Assessment

The Life Cycle Assessment (LCA) technique is used to analyze the combined ecological impacts related to every stage of life cycle of a service or product, including the obtaining of raw materials, the supply chain, the production process, the transportation emissions, as well as consumption and waste disposal (Klöpffer, 2012). LCA establishes an environmental profile of the system. LCA is a tool that can be applied; To recognize the most significant environmental burdens posed by the products and to identify the major hotspots processes that contributed more to the overall environmental burdens. LCA has four general phases (i) Goal and scope (ii) Life Cycle Inventory (LCI), (III) life Cycle Impact Assessment (LCIA) and (iv) Interpretation. Life cycle assessment (LCA) is an environmental sustainability tool that has been utilized to assess PET applications, substitute materials, and final use to find areas for ecological sustainability. As a result, it may and should be utilized as an analysis tool to promote the dissemination of sustainability information to the public, business community, and users (Gileno & Turci, 2021) The United Nations adopted the Sustainable Development Goals (SDGs) focusing on design that promotes sustainability, sustainable user data, manufacturing materials, and waste disposal, minimization, and prevention all benefit from LCA analysis (Hauschild et al., 2018). Due to Pakistan's inefficient waste management system compared to developed countries, the plastic recycling sector has more difficulties. As per Formigoni and Rodrigues, the reverse logistics connections, starting with the collection and scrap dealers, have flaws that are the causes of the post-consumer material supply being limited (2009). These flaws "do not enable a growth in recycled volumes, indicating the supply shortage of recycled goods and the interruption in the reverse channel," leading to the piling of waste in the environment. By applying LCA, PET bottles recycling improvement potential might be found. As defined by the Society of Environmental Toxicology and Chemistry, LCA is a technique use for assessing the environmental emission related to the process, product, or activity by detecting and assessing energy and resources utilized as well as waste input into the environment. LCA is the process of determining the impacts of a product or service across its entire life cycle, from raw material acquisition through final disposition (Mahmoudkhani, Valizadeh, et al., 2014). Applying LCA one may determine the best eco-friendly and sustainable way to get a service.

1.5 Problem statement

As per Pakistan environmental protection act 1997 and regulation on solid waste management, Pakistan (2010), the municipalities are sole responsible for waste collection, transportation, and disposal. All the municipal waste of Islamabad is collected and transported by Capital Development Authority (CDA) to dumping site at I-12 yet there are no proper segregation points for different type of waste and the recyclable waste like plastic, cardboard, glass, and metals are mixed with other solid waste and the recyclable waste become contaminated so there should be separated collection skips for recyclable waste. However, in regard of Pakistan, there are no significant numbers of studies which determine the environmental life cycle assessment of plastic recycling activities. Consequently, there has been no focus on the healthy occupation within the recycling units and there is no idea to the workers about the post work effects on the health of workers.

1.6 Research gap

There are various plastic waste recycling facilities across Pakistan for recycling different types of plastic into different products. These informal plastic recycling facilities also pose environmental impact (wastewater, Green House Gases emission, and human toxicity) during plastic recycling activities. No LCA study has been conducted in Pakistan to analyze the life cycle impacts and resources utilization by the recycling facilities in Pakistan. The issues related to the plastic management in Pakistan, current studies fail to account for the environmental impacts of plastic waste management technologies. Similarly, there is no such literature to devise most ecological friendly and sustainable choice for plastic waste management in Pakistan. Analyzing current environmental issues such as wastewater contamination and microfibers generated from fibers factories is important.

1.7 Objectives

- To determine the supply chain of PET bottles recycling and emissions to the environment, (Hotspots)
- To assess the potential environmental impacts of post-consumer PET bottle-to-fibre recycling.
- To compare the environmental impact of recycled fibre with the impact of virgin fibre

CHAPTER 2

MATERIALS AND METHODS

2.1 Study area

The PET bottles recycling process consists of two phases: in the first phase, PET bottles are crushed into flakes (Pre-treatment) and in second phase, PET flakes are melted into polyester staple fiber (post-treatment). Islamabad city for pre-treatment process and Sun fibre Pvt ltd located in Sunder industrial estate (SIE), Lahore for post-treatment of PET bottles recycling were purposely chosen. Islamabad is the capital of Pakistan having a population of 2 million and it is growing at a pace of 3.4 percent per year (Pakistan Bureau of Statistic 2017). A recent study found that 300 thousand households in the city produce about 1,000 metric tons of municipal solid waste every day. Islamabad metropolitan corporation (MCI) and capital development authority (CDA) handles the city's solid waste and transports it to a municipal dump site in Sector I-12. According to the CDA, only 1%of total collected solid waste is comprised of PET bottles which are collected by scavengers (*BASELINE ASSESSMENT OF PLASTIC WASTE MANAGEMENT IN ISLAMABAD, PAKISTAN*, 2019)

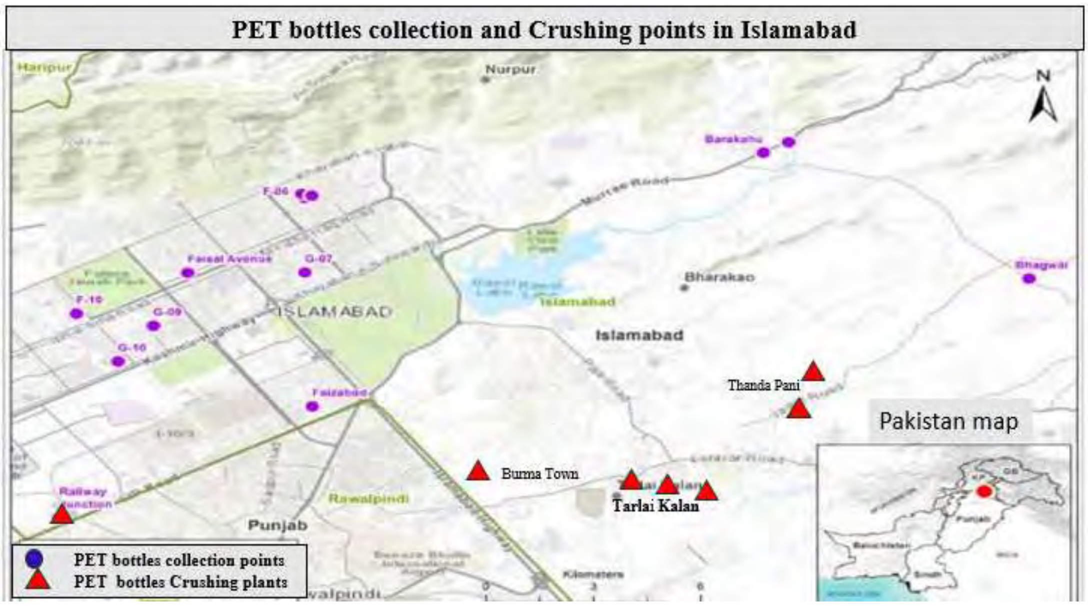


Figure : 2.1 Location map of PET bottles collection and crushing points in Islamabad.

Sun fiber (Pvt) limited; a recycled polyester fiber industry (rPSF) located at Sundar Industrial Estate (SIE) was purposively chosen for this study. This fiber industry recycles PET flakes into fibre. Its annual recycling capacity is 14000 tons and utilization capacity are 10500 tons per year. SIE has a latitude of 31.287 and longitude of 74.168. It comprises 1750 acres of land and was established in 2007. It is the first mega project of Punjab Industrial Estates (PIE) and was anticipated to be an island of facilitation for industrialist perspective. There are over 500 different industries which are manufacturing different products and contributing to the economy of Pakistan by generating 80 thousand of employments.

2.2 Mechanical Recycling

Mechanical recycling generally involves collecting waste, crushing, removing labels and dirt, reducing bottles volume by converting into flakes, extruding, and reshaping without changing the molecular structure. Mechanical recycling process is divided into two phases. (Pre-treatment and post-treatment).

2.2.1 Pre-treatment (Flakes manufacturing process)

According to the CDA, 1% of total collected solid waste is comprised of PET bottles which are collected by scavengers. Almost all the recycled PET bottles are collected by scavengers and are sold to scrape dealers and PET bottles crushers located at various sectors of Islamabad. Seven small PET bottles crushing plants were visited in Islamabad. Every plant, an average receives one ton of PET bottles from various scrape dealers across the city. These bottles are segregated according to their color, crushed, and are converted into small pieces called flakes. The bottles are crushed to reduce the volume and transportation cost. The flakes undergo cleaning using a wash boat. An average of four thousand liters of water is consumed in washing of one-ton flakes. Caustic soda (NaOH) is used to remove oil and clean the flakes properly. Approximately 10 kgs of caustic soda are used in washing line per ton of PET flakes. The flakes are then dried. About 10-15% of waste (PE labels and lids) is discarded during the pre-treatment process. These flakes are packed in bags and transported to large recycling industries (Lasani fibre, E-vision, Khalis fibre, Sun fibre (Pvt) Limited) located at Sundar industrial estate, Lahore. The flakes are recycled into polyester staple fibre (rPSF). All the data concerning fuel, water and washing chemicals consumption are collected from the plants.

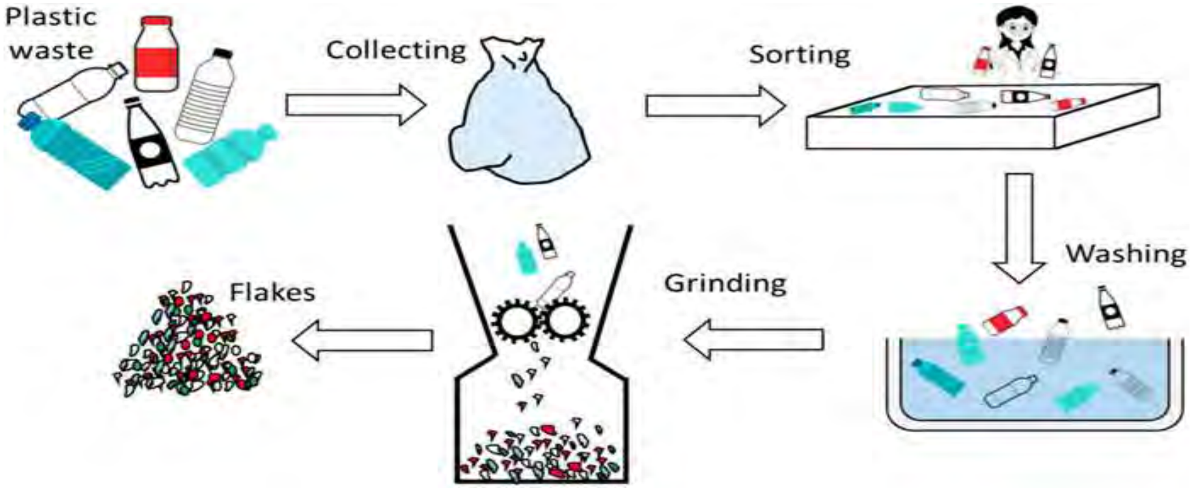


Figure : 2.1 Pre-treatment (flakes production)(Brouwer et al., 2019)

Table: 2.1 Energy and resource consumption in 1 t PET bottles recycling

Parameters (inputs)	Values /t
PET bottles waste	1200 kg
Pre-treatment (flakes production)	1100 kg
Electricity consumed	80 kwh
Caustic soda (NaOH) in washing line	10 kg
Water consumed	3000 L
Diesel used in PET bottles collection	6 L
Coal in steam production and boiler	100 kg
Plastic waste (PE)	100 kg
Post-treatment (fibre production)	1000 kg
Electricity consumed	420 kwh
Diesel in flakes transportation (760km)	18 L
Water used	200 L or kg
Winding plastic waste	100 kg

Figure : 2.2 Pre-treatment of PET bottles

2.2.2 Post-treatment (production process)

For post-treatment of PET bottles flakes, Sun fiber (Pvt) limited, a recycled polyester fiber industry (rPSF) located at Sunder Industrial Estate (SIE) was purposely chosen for this study. This fiber industry recycles PET bottles flakes into staple fibre. Its annual recycling capacity is 14000 tons and utilization capacity are 10500 tons per year. The flakes are transported to Lahore through medium trucks (payload 10 tons) for post treatment. Recycled PSF are utilized for technical end use or can be blended with cotton to make fabrics in textile Mills. The flakes are dried in vacuum drier (150 C^0) to remove the moisture and add some brightening agent. The semi-molten substance is fed into extruder for melting under 260 C^0 temperature. After this, the molten substance passes through the spinneret to produce filaments. The filaments are collected in oil cans to make the filaments soft. After that, the tows of fibres pass through hot (60-80C^0) Draw bath, and draw line (stretcher), After that, the tows pass through relaxing drier, then the tows are cut into fixed length fibres. After cutting, the short fibers are pressed into bales of 225kg each and then sent to the storage by fork lifter.

Figure : 2.3 Post treatment

Table : 2.2 Fuel required for transportation of PET flakes to rPSF industries (Lahore).

S. N	Inputs /ton	
1.	Vehicle capacity	10 tonnes
2.	Vehicle mileage (diesel)	6 km/L
3.	Distance travelled (approx.)	760km(two-way)
4.	Fuel required for transporting 10 tons of PET flakes	126 L
5.	Fuel required (diesel) for transport 1 ton of flakes.	12.6 L
6.	Total transportation fuel (diesel)	18 L

Figure : 2.4 PET bottles recycling processes flowchart.

All the data concerning PET bottles recycling process and input materials and energy were collected. For recycling one ton of flakes to fibers, an average of 200 liters of water, 420 kwh electricity, 100 kilograms of coal for heat and steam production, 18 liters of fuel (diesel in transportation) are consumed in post-treatment process.

2.3 Data collection

Most of the input and output data were collected from the initial information available on real sites in Pakistan. Primary data about PET bottles collecting, shredding, washing, transportation and recycling were collected from local sites in Pakistan by different sources including questionnaires, survey, visits, and interviews with the scrape dealers, PET bottles crushers, recyclers, industries managers and experts. Some data were obtained from the literature due to the lack of governmental information. Post-consumer PET bottles supply chain, use of energy and means of transportation data were collected from seven local PET bottles pre-treatment plants located at different points of Islamabad and the data about post-treatment was obtained from Sun fiber (Pvt) Limited in Sunder industrial estate, Lahore. This data was collected through questionnaires survey, interviews, and field visits whereas secondary data was taken from the literature review and publications and used SimaPro 9.4 software tool for LCA analysis. One of the advantages of simaPro software is its access to broad and efficient databases. The primary data was combined with secondary database and modeled using CML 2000 v.2.05 methodology and a cumulative exergy demand indicator present in the SimaPro version 9.4 software.

2.4 Phases and Framework of LCA

Method: CML 2 baseline 2000 v2.05 was used**.** LCA has four general phases, (1) Goal and scope definition, (2) Life cycle inventory (LCI) (3): Life cycle impact assessment (LCIA) and (4): Interpretation (ISO14040/44). In goal and scope definition, different parameters such as functional unit and system boundary and assumptions along with the objectives are defined. In the 2nd phase all the inputs and outputs which include the inputs of all raw materials such as energy, water, and the emissions to the environment (Hotspots). The 3rd phase is the life cycle impact assessment which means to evaluate the significance of potential environmental impact based on inventory data. Interpretation is the 4th and final phase of LCA which is used to derive a meaningful conclusion from LCA results.

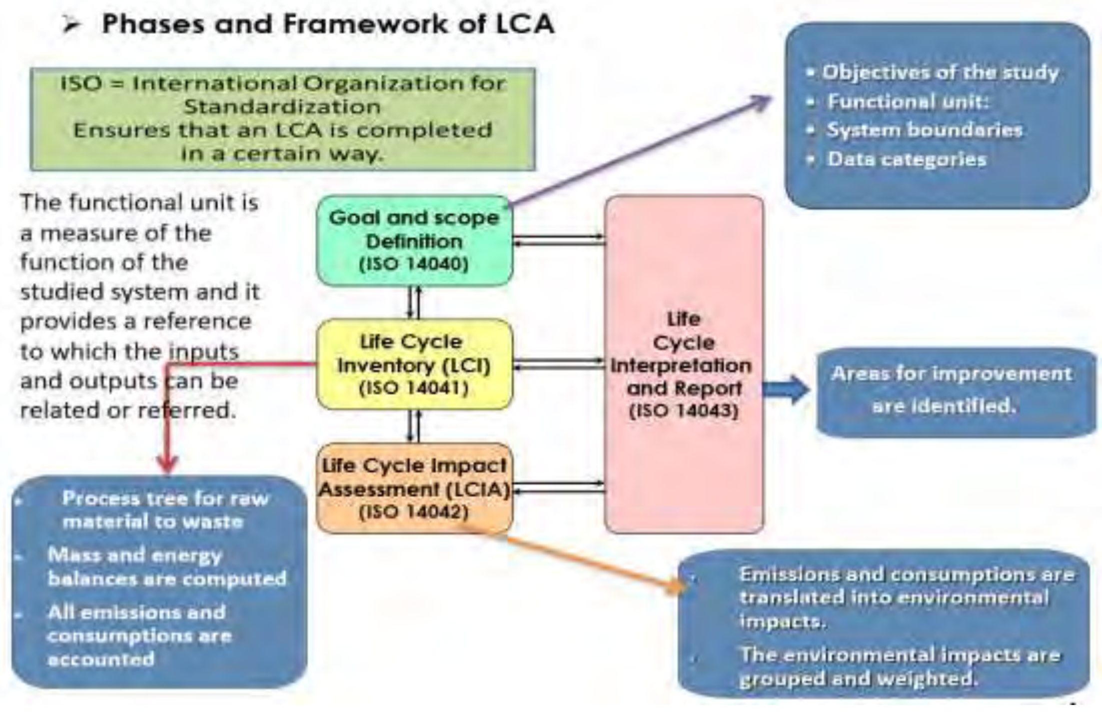


Figure : 2.5 Phases and Framework of LCA

2.4.1 Goal and scope

The main aim of this study was to examine the environmental impacts of different input materials and energy of PET bottles recycling process (pre-treatment and post-treatment) and to compare the recycled PET fibre result with virgin PET fibre in Pakistan. The first step that will decide the system boundary is defining the goal and scope. Inventory data collection and analysis is the next step. LCA was used to identify the environmental emissions (hotspots) in the supply chain of post- consumer PET bottles included inventory items, recycling processes, energy use and environmental impact category that contributed to the mechanical recycling of rPSF which can be regarded as substitute for virgin polyester fibre and a credit for the avoided production of equivalent virgin fibre from petrochemical. According to Global Climate Risk Index (2021), Pakistan was ranked as the 8th most effected country in the world vulnerable to long–term climate risk. Therefore, this study can hopefully take a step toward reducing GHG emission by decreasing the consumption of fossil fuels as valuable and non-renewable resources for the country.

Table : 2.3. Product system in this study, comparing type of fibre and application

Technology	Recycling type	Reference
Technology	Mechanical recycling	Single use virgin PET
Current technology level	Large scale production	Large scale production
Inventory data	Sun fibre (Pvt) Limited	Literature data
Geographical scope	Asia, Pakistan	Western Europe
Type of fibre	Staple fibre (rPSF)	Staple and filament
Application	Technical end use	Non-woven and apparel

System boundary and functional unit

The system boundary ranges from post-consumer PET bottles collection by scrape dealers and municipalities to the recycling facilities. The system boundary is from cradled -to-factory gate because in this study the system boundary starts from the point where post-consumer PET bottles are discarded by the consumers and ends when these bottles are recycled into new products (Cut-off Rule)(Chairat &

Gheewala, 2023) . The system boundary in this study includes collection, transportation, and recycling process of post-consumer PET bottles waste to rPSF production. For virgin PET production, this includes all the steps from raw material extraction, transportation, and followed by all processing steps until the product (rPSF) is delivered at the factory gate.

The functional unit is responsible for evaluating all analysis, including bottle collection, flakes production, transportation, and production of one-ton recycled PSF. In this study the functional unit is one metric ton of PET fibre. The chosen functional unit shows that the rPSF is like virgin PET fibre (Shen et al. 2010).

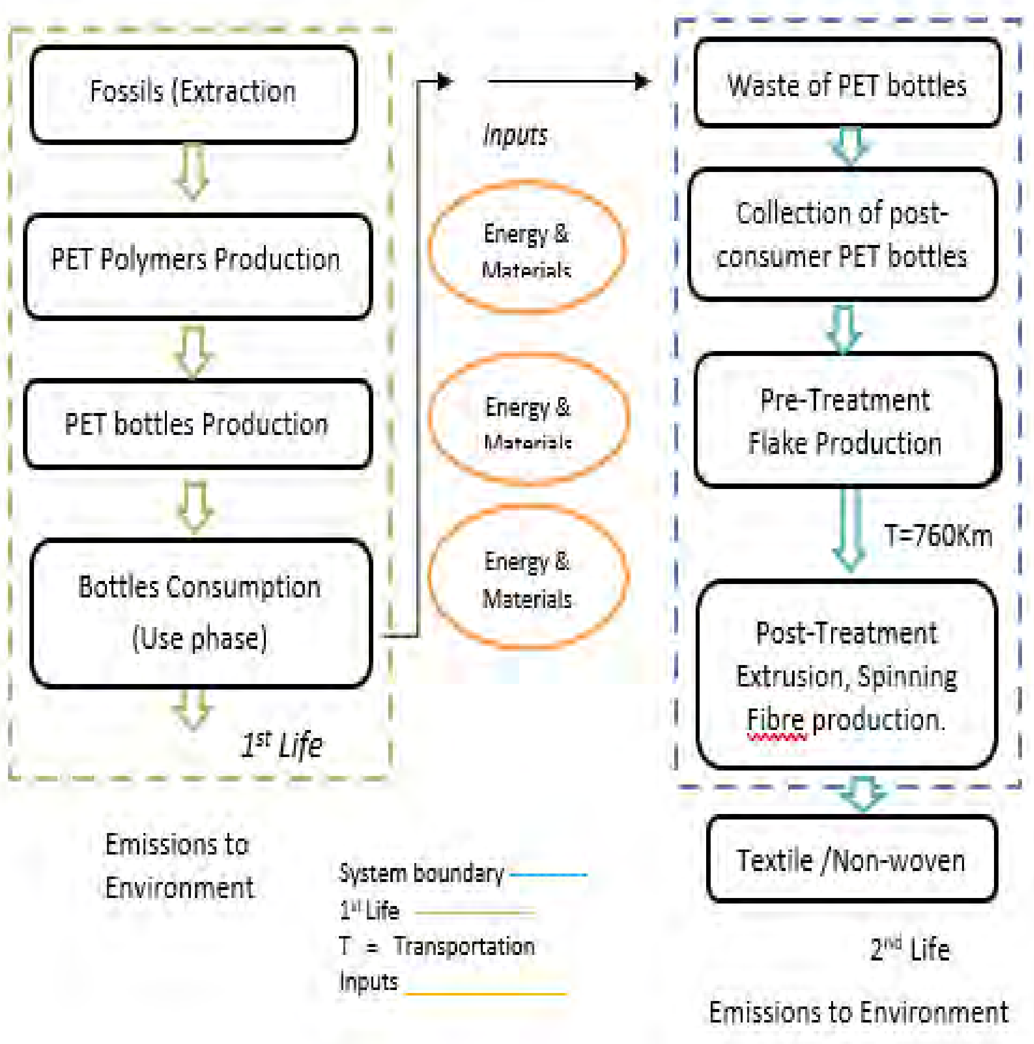


Figure : 2.6 System boundary

Table : 2.4 Data sources of this study

Data	Sources	Noe
PET bottles-to- fibre recycling	Collected from rPSF producers (Sun fibre Pvt Ltd.)	Site specific for year 2022
Grid electricity	Eco invent v2.0	Country specific (GLO)
Transportation distance	Collected from PET recycling factories	10-ton lorry for road transportation
Virgin polymer production	Plastic Europe eco-profile (bousted 2005a, b)	Western Europe polymer production
Energy use for fibre spinning process (for melt-spinning virgin PET fibre)	Assumption based on (Brown et al., 1985):650 kWh electricity and 5000 Mj heat from fossil fuel per ton fibre	The data has been cross-checked by PET recycling factories

2.4.2 Life cycle inventory (LCI)

The inputs to the system are the energy and materials, such as PET bottles waste, caustic soda (NaOH), diesel fuel in the transportation trucks and process of equipment, and final waste flow and the energy supply such as electricity and coal heat for process operations. The emissions to water, air and soil are the outputs of the system which are caused from waste transportation and other machines operation. The integrated inventory data for various stages of the recycling was checked for accuracy and if any missing data found the same was either revised or assumptions were made related to the gap. Input and output data sets were checked and appropriated for all the material and energy flows involved in the study of the life cycle.

2.4.3 Life cycle impact assessment (LCIA)

The environmental impact categories of the LCA are chosen based on the requirement of the study**.** Numerous environmental impacts categories were supposed for life cycle impact assessment. The selection of the impact categories is dependable on the purpose and scope of the study. The considered environmental impact categories for this study were global warming potential (kg CO_2-Equivelent), ozone layer depletion potential (Kg R11-Equiv), acidification potential (kg SO_2.Eq), freshwater aquatic toxicity potential (kg D-B-eq), eutrophication potential (kg phosphate-eq.), abiotic depletion potential (Kg D-B-eq), human toxicity potential (kg-D-B-eq) and photochemical oxidation (kg C_2H_4Eq)(Klöpffer, 2012)

The characterization of environmental impacts is done as below.

The steps of this phase are:

- **Classification:** The inventory analysis results are related to different impact categories**.**
- **Characterization:** The quantification of impacts categories using characterization factors obtained from scientific models, thereby enabling the transit from a qualitative to a quantitative assessment.

Equation (1) is employed in the characterization step:

$$\mathbf{EP\ (j)i = Q \times EQ\ (j)\ i} \qquad \mathbf{(1)}$$

where EP(j)i is the environmental impact of substance i with respect to the impact category j, Q is the quantity of substance i, and EQ(j)i is the contribution of substance i to impact j.

Environmental impacts of the current PET bottles recycling were assessed by seeing their collection, transportation, crushing, washing of PET flakes, washing detergent used, water quantity used, energy consumption quantity and types (electricity, coal, diesel) and their emission to air, water, and soil.

Abiotic depletion potential

Abiotic deletion term is used as a less availability of natural resources (fossil fuel and water etc.). The depletion of abiotic natural resources is calculated as in equation 1 (Schneider, Berger et al. 2015). Abiotic depletion is equivalent to Sb.

$$EAB = (ADP+R) \qquad (1)$$

Where

EAB =Abiotic depletion Exhaustion (Kg eq Sb)

ADP=Abiotic Depletion Potential (Kg eq Sb/Kg of resources consumed)

R= Resources consumed (Kg)

Acidification

For its acidifying consequence, the Acidification is taken in term of the SO_2 potential. Ammonia and nitrogen oxides also have taken part in acidification. Acidification is calculated in Equation 2:

A =AP x EA (2)

Where

A= Acidification (Kg)

AP= Acidification Potential

EA = Emission to Air (Kg

Eutrophication

Phosphate ion (PO_4^-) is the component responsible for eutrophication which is generally caused due to runoff water. The eutrophication is taken 1 for PO_4. The acidification probability is calculated by the equation 3:

EP = NP x EA (3)

Where

EP =Eutrophication potential (Kg PO4^- eq)

NP = nitrification potential

EA= emission to air (Kg)

Global warming potential

Global warming is the continuous increasing of world temperature which is caused by the result of greenhouse gases (GHG) emission. Generally, 100 years are taken to account the global temperature increase and contribute to the global warming. It has Equation 4:

GW = (GWP 100 x EA) (4)

Where

GW = Global warming (Kg CO_2 equivalent)

GWP100 = Global Warming Potential for 100 year

EA = Emission to Air

Ozone layer depletion

CFCs chlorine, Fluorine, Carbon is mainly responsible for ozone layer breakdown. These gases are released due to the consumption of such product or equipment or activities which release these gases, and it is calculated by the Equation 5.

OD = (ODP x EA) (5)

Were

OD = Ozone layer depletion (Kg CFC-11 Eq)

ODP = Ozone layer depletion

EA = Emission to Air (Kg)

Human toxicity potential

Human Toxicity is caused by the emission of various toxic gases such CFCs. Dirty dozen twelve persistent organic pollutants which are released into the environment such air, water and soil and affect human population. Human Toxicity is calculated by the following Equation 6:

HT = (A x EA) + (HCW + EA) (6)

Where

HT = Human toxicity (kg 1,4-DB eq)

HCA = Human toxicological classification value for air (Kg / Kg)

HCW = Human toxicological classification value for water (Kg / Kg)

EA = Air borne Emission (Kg)

Terrestrial toxicity

This category included the substances which are responsible for the toxicity of both plants and animals (flora and fauna). Usually, heavy metals are responsible for damaging the marine and land eco-systems. Therefore, their toxicity level score has been established in water and soil. (Sloof and Wolterbeek 1992). It is calculated by equation 7:

E(A) = (ECA x EW) (7)

Where

E (A) = Aquatic toxicity (kg 1,4 DB eq)

ECA = aquatic ecotoxicity (m^3 / kg)

EW = Waterborne Emission (Kg)

And

E (T) = (ECT x EL) (8)

Where

E (T) = Terrestrial toxicity (kg 1 ,4-DB equivalent)

ECT = Terrestrial ecotoxicity

EL = Land borne Emissions (kg)

Photochemical oxidation

Twelve persistent organic pollutants (dirty dozen) which are released into the environment and the presence of volatile organic compound produce O_3 gas in the air. A variety of gases cause photochemical oxidization, but ethane (C_2H_6) is considered as standard 1 for photochemical oxidation. Equation for its calculation is as follow.

S = (POCP x EA) (9)

Where

S = Terrestrial Toxicity (kg C_2H_4 Eq)

POCP = photochemical ozone creation potential

EA = Emission to Air

2.4.4 Interpretation of the results

The final and last phase of LCA framework is the interpretation of the results from the inventory analysis and life cycle impact assessment. The interpretation of the results is performed with the reference of the goals and objectives of the study (Klöpffer, 2012).

2.5 The significance of the study

This LCA study will help identify the significance of plastic waste management and recycling activities of the country. Moreover, it will help in finding emission hotspots of the supply chain for PET bottles recycling causing higher environmental burden and to identify the activities involved in such a high environmental emission. This will help in suggesting policymakers the improvement opportunities regarding plastic waste recycling and management and suggest a definite plastic waste recycling strategy for each step.

2.6 Analysis

Simapro 9.4 software is an important assessment tool, developed by Pré Sustainability, and was applied. SimaPro software is the leading LCA software tool that has been used for more than 25 years by industries and academics in the world. It uses two types of inventory data, primary data, and secondary data. The primary data includes the basics of inputs for production such as the amount of PET flakes and other resources used to manufacture products such as the production of rPSF. The secondary data, however, comes from the database which includes the impacts caused by production that much raw material (in our case PET bottles waste) and all other input materials such as chemicals (NaOH) at every stage. For secondary data, Eco-invent database linked with the software is the most commonly used life cycle inventory database worldwide(Kurokawa et al., 2003)**.** The agencies such as NREL, Eco-invent, provide these databases and most of the LCA tools providers such as GaBi, Simapro 9.4, Umberto, etc. have their own datasets or other databases can be imported in the same for different materials and energy flow.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Results

The midpoint impact categories have different units and cannot be compared. So, the percentage bares are usually used to compare them. The following impact categories are usually taken. Global warming potential (kg CO2 equivalent), abiotic depletion potential (kg Sb eq), human toxicity (kg 1,4-DCB eq), ozone layer depletion (kg CFC-11-eq), acidification (kg SO2-eq), freshwater and marine water ecotoxicity and photochemical oxidation were selected as impact categories to illustrate the environmental impact of PET bottles recycling. Pre-treatment phase of waste was the leading factor of global warming and human toxicity categories, and the post-treatment phase was dominating in other impact categories. The acquisition of raw material phase had no impact at all. Whereas, crushing of bottles and extruding (heating) processes emit solid plastic waste. Global medium electricity mix dataset was used for electricity inputs. The recycling process was divided into two treatment processes (Pre-treatment and Post-treatment). Pre-treatment of PET bottles waste (PET bottles crushing and flakes washing and transportation) post-treatment process (Flakes extruding, spinning, draw line, drying and rPSF production).

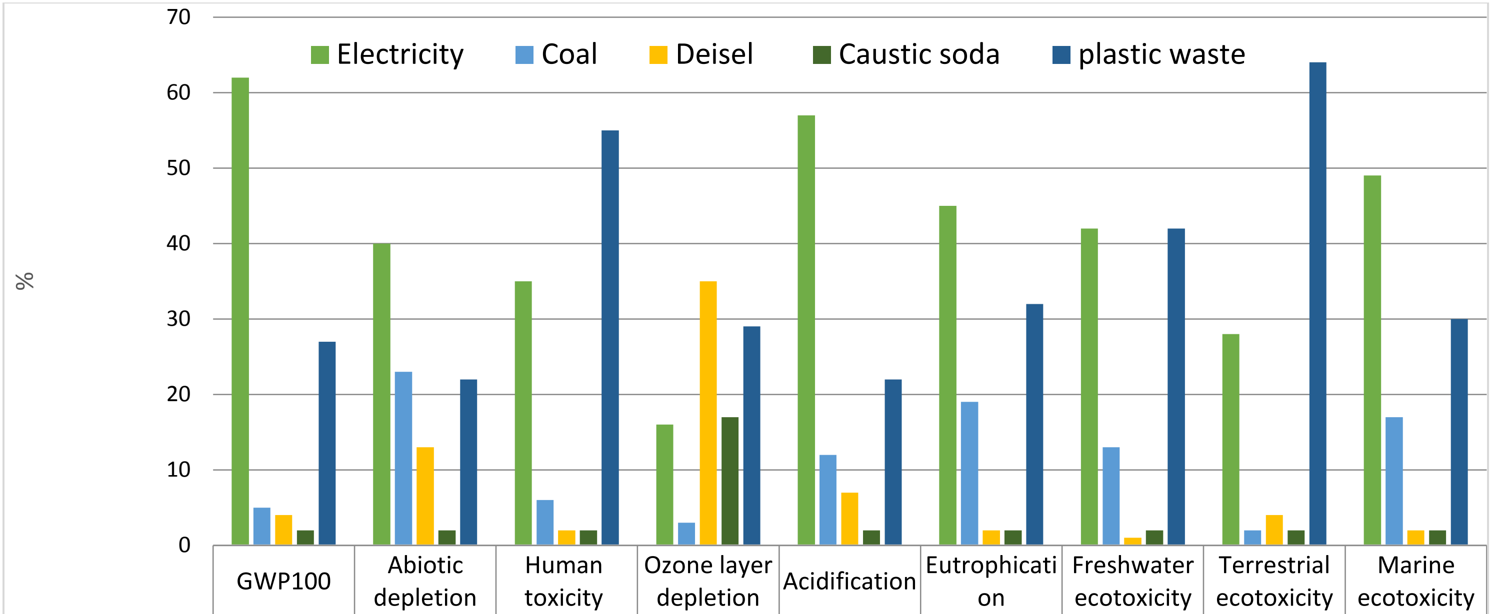
3.1.1 Life Cycle Impact Assessment Results

In life cycle impact assessment (LCIA), the inventory which shows all the inputs materials and energy requirement and the output or emissions into environment by the recycling processes are translated into environmental impact. The results are referred to the LCA midpoint results. In this section, all the emissions from the recycling processes (pre-treatment and post-treatment) of the study area are discussed. The characterization results per tone of recycled polyester staple fibre for each impact category and parameter are reported in Table 3.1.

In addition, normalization was performed using CML normalization factor 2000. Normalization of the result shows the relative contribution of the product system to the impact categories at the global level. It does not have a weighting of the impact categories and has only indication to which extent the product system contributes to the overall environmental burden of a region for a given year (Table 3.2).

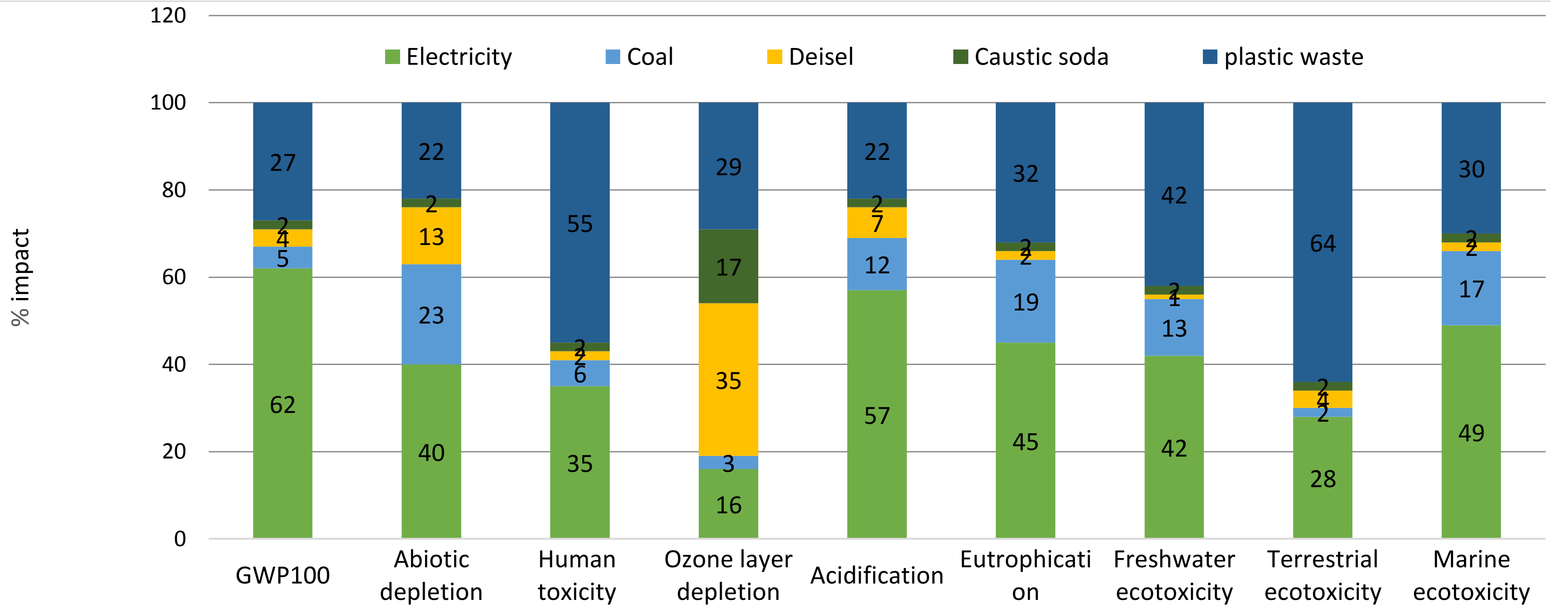
Table : 3.1 LCIA results of recycled PSF production. Values are presented per functional unit

Impact category	**Unit**	**values**	**Plastic waste**	**Caustic soda**	**Diesel**	**Coal**	**Electricity**
Abiotic depletion	kg Sb eq	7.97	23%	1%	13%	23%	40%
Acidification	kg SO_2 eq	3.32	22%	2%	7.2%	13%	56%
Eutrophication	kg PO_4^- eq	1.82	33%	2%	2%	18%	45%
Global warming (GWP_{100})	kg CO_2 eq	701	27%	2%	4%	5%	62%
Ozone layer depletion	kg CFC-11 eq	7.62E-05	29%	17%	36%	2%	16%
Human toxicity	kg 1,4-DB eq	763	55%	2%	3%	5%	35%
Fresh water ecotoxicity	kg 1,4-DB eq	429	41%	2%	1.2%	13%	42%
Marine aquatic ecotoxicity	kg 1,4-DB eq	705754	30%	2%	2%	17%	49%
Terrestrial ecotoxicity	kg 1,4-DB eq	4.33	66%	1.4%	4%	1.4%	28%
Photochemical oxidation	kg C_2H_4 eq	0.16	31%	1%	6%	13%	50%



	GWP100	Abiotic depletion	Human toxicity	Ozone layer depletion	Acidification	Eutrophication	Freshwater ecotoxicity	Terrestrial ecotoxicity	Marine ecotoxicity
Electricity	62	40	35	16	57	45	42	28	49
Coal	5	23	6	3	12	19	13	2	17
Deisel	4	13	2	35	7	2	1	4	2
Caustic soda	2	2	2	17	2	2	2	2	2
plastic waste	27	22	55	29	22	32	42	64	30

Figure : 3.1 Percentage bars of impact categories for 1 t PET bottles recycling

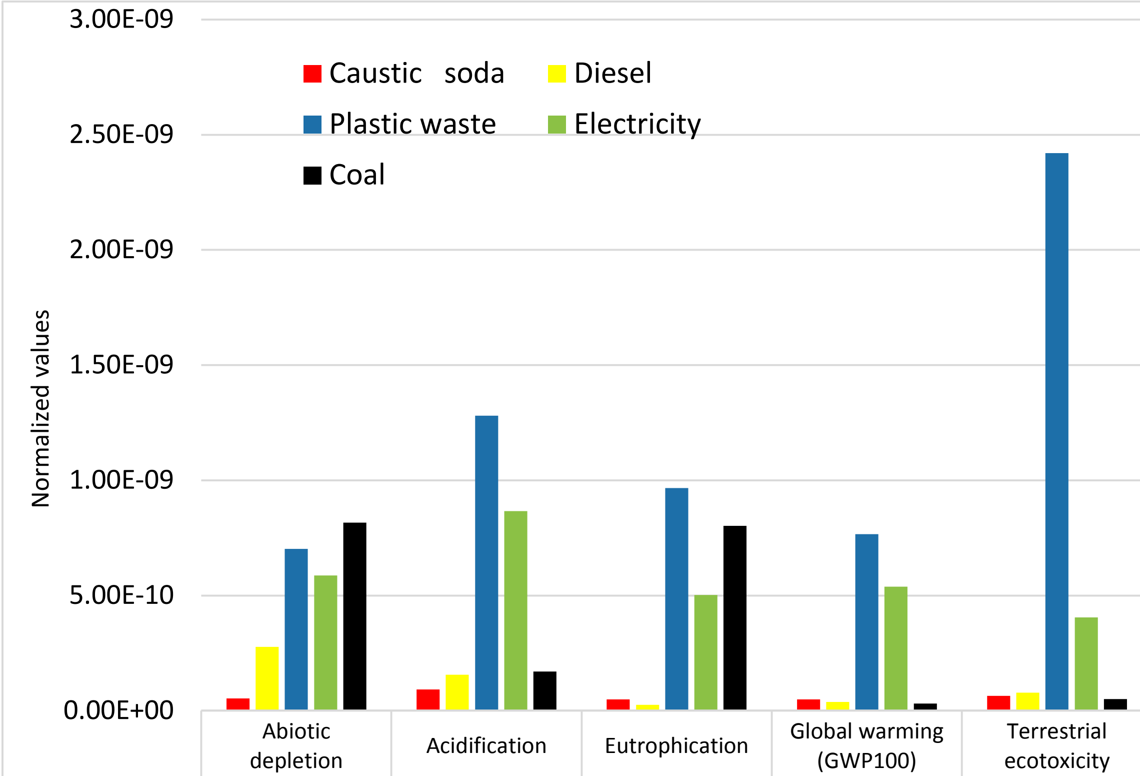


	GWP100	Abiotic depletion	Human toxicity	Ozone layer depletion	Acidification	Eutrophication	Freshwater ecotoxicity	Terrestrial ecotoxicity	Marine ecotoxicity
plastic waste	27	22	55	29	22	32	42	64	30
Caustic soda	2	2	2	17	2	2	2	2	2
Deisel	4	13	2	35	7	2	1	4	2
Coal	5	23	6	3	12	19	13	2	17
Electricity	62	40	35	16	57	45	42	28	49

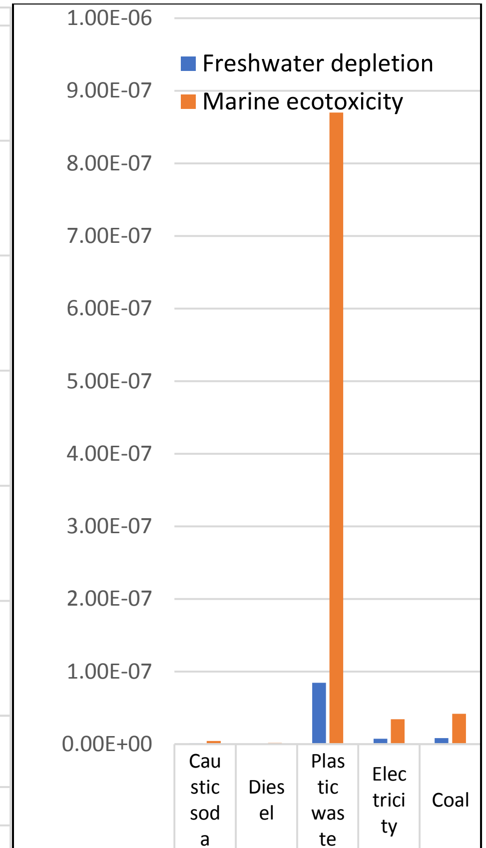
Figure : 3.1. Impact characterization of 1 t PET bottles recycling

Table : 3.2. Normalized impact categories for 1 t PET fibre

Impact categories	Values
Abiotic depletion	2.44E-09
Acidification	2.57E-09
Eutrophication	2.34E-09
Global warming (GWP_{100})	1.42E-09
Ozone layer depletion (ODP)	4.76E-11
Human toxicity	6.32E-09
Fresh water aquatic ecotoxicity	1.02E-07
Marine aquatic toxicity	9.52E-07
Terrestrial ecotoxicity	3.02E-09
Photochemical oxidation	4.96E-10



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Terrestrial ecotoxicity
Caustic soda	5.28E-11	9.19E-11	4.93E-11	4.97E-11	6.40E-11
Diesel	2.77E-10	1.56E-10	2.53E-11	3.78E-11	7.85E-11
Plastic waste	7.02E-10	1.28E-09	9.66E-10	7.66E-10	2.42E-09
Electricity	5.87E-10	8.67E-10	5.02E-10	5.38E-10	4.05E-10
Coal	8.17E-10	1.70E-10	8.03E-10	3.15E-11	5.03E-11



	Caustic soda	Diesel	Plastic waste	Electricity	Coal
Freshwater depletion	1.11E-	2.80E-	8.45E-	7.53E-	8.35E-
Marine ecotoxicity	4.21E-	1.70E-	8.70E-	3.41E-	4.18E-

Figure :3.2 Normalization of the impact categories

Table : 3.3. LCA result for 1 t of recycled PET fibre from cradle-to-factory gate and their comparison with virgin fibre

Recycling route (world)	Mechanical recycling		Virgin-PET fibre
Name of industry	Sun fibre Pvt Limited, Lahore, Pakistan	L Shen et al. (2010) Wallman Netherland	N/A
Fibre type	Staple	Staple	Staple
Global warming potential 100a kg $CO_{2\ eq}$	701	960	4060
Abiotic depletion (kg Sb eq)	7.97	6	45
Acidification (kg SO_2 eq)	3.32	3	21
Eutrophication (kg PO_4^{-2} eq)	1.82	0.8	1.2
Human toxicity (kg 1,4-DB eq)	762	362	4393
Fresh water aquatic eco-toxicity (kg 1,4-DB eq)	429	296	58
Terrestrial ecotoxicity (kg 1,4-DB eq)	4.33	7	12
Photochemical oxidation (kg C_2H_4 eq)	0.16	0.2	1.0

Source: Shen et al., (2010)

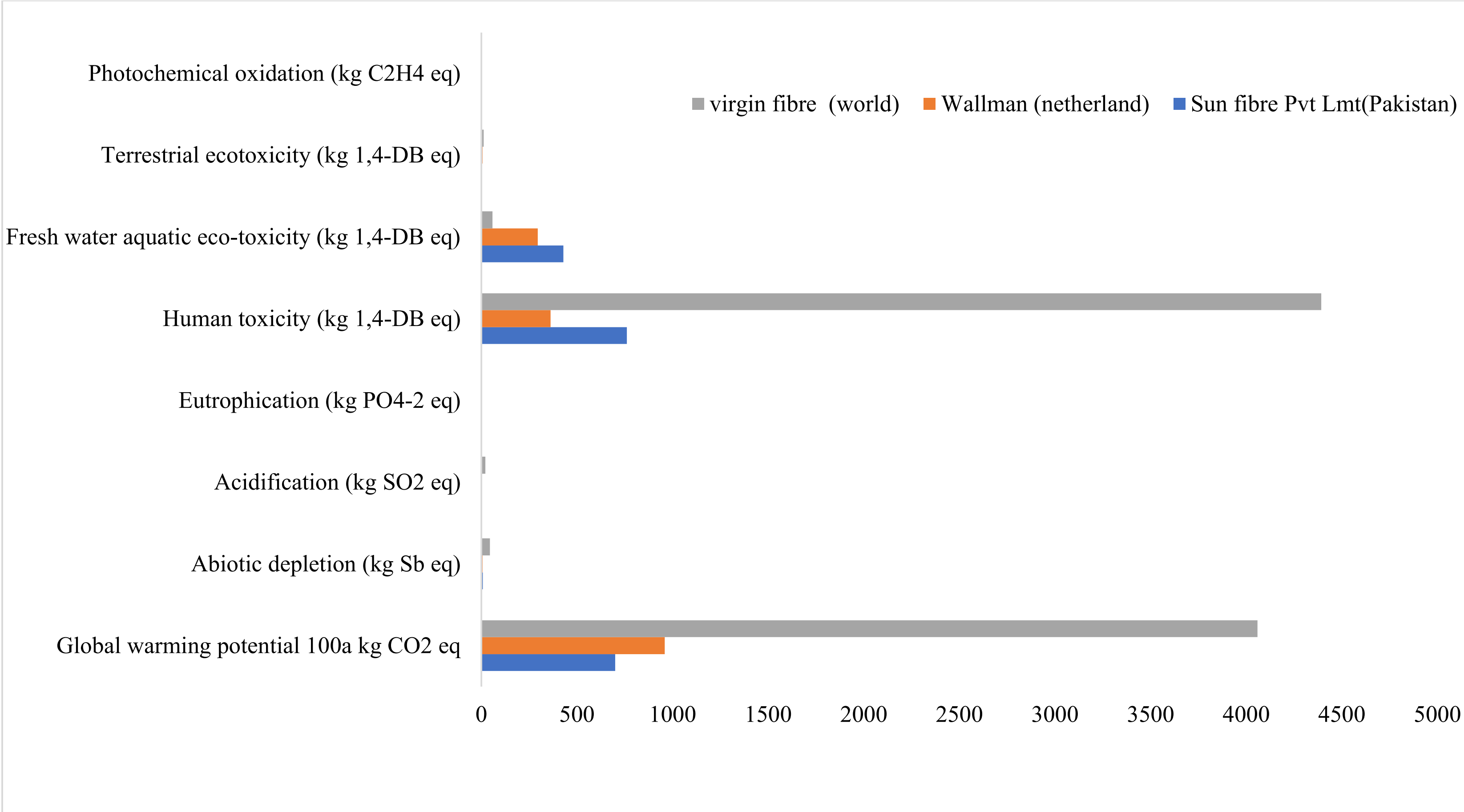


Figure : 3.3 Comparing impact categories of this study with other study and virgin fibre production.

3.1.2 Global Warming Potential

Global warming impact of 100 years was considered and calculated for different activities in this study. The numerical value of total global warming impact caused by all the activities of pre-treatment processes of flakes was 967 kg CO_2 eq. Among this high value of GWP-100, the recycled plastic waste burning (933 kg CO_2 eq) and diesel (14.33 kg CO_2 eq) consumed in vehicles caused the highest global warming and electricity used showed the impact of 7.22kg CO_2 eq. caustic soda had the global warming impact potential of 12.54 kg CO_2 eq. The higher value of GWP from the fuel burning was due to the large quantity of fossil fuel used during PET bottles transportation. The quality of fuel also affects the emission of pollutants from fuel burning during operational activity. The substances which cause global warming are carbon dioxide, carbon monoxide, dinitrogen monoxide, methane, and Sulfur hexafluoride. The total emission of CO_2 from all activities by recycling one ton of bottles into flakes was 912.3 kg CO_2 eq. This global warming impact can be reduced by improving the quality of fuel used. This can also be achieved by decreasing the amount of fuel used by using efficient means of transportation and for this purpose, the distance between waste bottles collection points and recycling facilities must be reduced. The global warming impact can also be lowered by using alternate fuel as compared to current fuel used. The current fuel used is gasoline along with diesel in some high-capacity vehicles and if we replace such type of fuel by Compressed Natural Gas (CNG) then it will be very helpful in decreasing global warming impacts from the transportation section. Simon et al., studied PET and noted that the recycling option led to the least greenhouse gases (GHG) emissions. Other studies show that the molecular structure of PET plastic does not change for mechanical recycling and has no greenhouse gases emissions.

3.1.2 Abiotic depletion Potential (ADP)

The characterization results showed that total abiotic depletion caused by the recycling of one-ton post-consumer PET bottles waste into fibre process i, e bottles transportation, crushing and washing and drying of flakes and extrusion was 7.97 kg Sb eq. Among all these activities marine aquatic eco-toxicity due to the combined impact of the caustic soda (NaOH) used for washing of flakes showed higher values which were 13420.9 kg 1,4 D-B eq and 210644 kg 1,4-D-B eq respectively. The ADP caused by diesel used for transportation in vehicles, electricity and coal used in PET bottles recycling process were 1.02 kg Sb eq, 3.21 kg Sb eq ,1.82 kg Sb eq respectively. Among these parameters, the caustic soda showed less ADP (0.09kg 1,4-DB eq). The higher ADP shown by burning of fuel was due to the emission of major pollutants such as cadmium, chromium, lead, manganese, molybdenum, nickel, phosphorus, sodium sulfate, sulfur, and zinc. The fuel burning activities showed a higher value of all these emissions. PET bottles waste collection from different households and transportation to waste recycling facilities play a major role because a good waste management strategy needs a precise amount and definite type of waste which is to manage. In any waste management plan, the transportation portion causes greater environmental impacts due to the type and amount of fuel used in vehicles during waste collection and transportation.

3.1.2 Acidification Potential (AP)

The results of acidification potential of all the activities of the pre-treatment showed a total of 8.03 kg SO_2 eq, the plastic waste caused a maximum acidification potential of 7.79 kg SO_2 eq. All other activities including caustic soda (NaOH) and diesel used in the transport caused an impact of 0.06 kg SO_2 eq and 0.16 kgSO_2-eq respectively. The electricity usage caused the AP impact of 0.02 which is the lowest. The AP of all the activities was due to higher emission of caustic soda (NaOH) and plastic waste and SO_2 from burning fuel. These substances contributed to total AP caused due to different activities of PET bottles. The impact category, eutrophication, has a total value of 0.98 kg PO_4 eq. Among this, the total value of eutrophication, the plastic waste contributed to the major part which was 0.93 kg PO_4 eq. The other activities such as caustic soda, electricity usage and use of diesel showed impact of 0.02 kg PO_4 eq, 0.01 kg PO_4 eq, 0.02 kg PO_4 eq, respectively. In eutrophication impact categories, the major contributors were the production of residual plastic waste in different washing and crushing activities and consumption of fossil fuel in transportation. The major substances and their total concentrations, which caused eutrophication potential were plastic waste and ammonia. 10.79g, suspended solid 38.04kg, sulphate 837g respectively released pre-treatment activities. The higher value of nitrate was due to fossil fuel (5.2 E -5 kg PO_4 eq) consumed in all vehicles used for PET bottles transportation. Similarly, the other substances which are emitted during different activities also cause eutrophication impact.

3.1.4 Ozone Layer Depletion

Ozone layer depletion potential is calculated in kg CFC-11 eq. The total ozone layer depletion potential of all activities from PET bottles collection to flakes production process was 3.93E -05 kg CFC-11 eq. From all the activities of pre-treatment of PET bottles, the fuel burning in transportation fleet showed higher impacts of 1.98E-05. The OLD potential caused by other processes are from electricity used was 3.18E07, plastic waste 6.54E - 06, In this impact category, the recycling of PET waste and electricity caused highest impacts as compared to other activities. The fuel used plays a major role in these impact categories. This high contribution is due to emission of different pollutants such as HCFC - 140 (1.2E - 10 kg CFC - 11 eq) , CFC - 113 (4.7E 09 kg CFC - 11 eq) , CFC - 114 (1.11E - 08 kg CFC - 11 eq) , HCFC - 124 (4.3E - 12 kg CFC - 11 eq) , HCFC - 22 (9.2E - 09 kg CFC - 11 eq) , CFC - 12 (1.11E - 08 kg CFC - 11 eq) , CFC - 10 (2.3E08 kg CFC - 11 eq) , and CFC - 11 (7.4E - 11 kg CFC - 11 eq). According to Martin ozone layer depletion is caused by the release of de-halogenated gases and hydrocarbons (in the incineration process) during PET waste treatment (Martin et al., 2021).

3.1.5 Human Toxicity Potential

The human toxicity potential (HTP) is calculated in kg 1,4-DB eq. The total impact of HTP caused by all the activities of PET bottles pre-treatment was equal to 358 kg 1,4-DB eq. In this high value of HTP, the caustic soda (NaOH) used in washing of flakes equal to 1654kg 1,4-DB eq and recycling plastic waste 346 kg 1,4-DB eq. This caustic soda (NaOH) was produced throughout the cleaning process of recycling facilities. The other activities also played role in such high value of human toxicity potential. The electricity showed human toxicity potential equal to 10.9 kg 1,4 -DB eq, caustic soda showed an impact of HTP in the range of 16.5 kg 1,4-DB eq. In this impact categories, the caustic soda and the plastic waste emission had the highest impacts on humans' health than the other material and energy and this is due to the emission of sodium hydroxide from washing of flakes. The concentration and types of such pollutants depend on types and the amount of washing agents used in washing of

PET bottles flakes. This high concentration of pollutants emissions into water from cleaning and shredding of flakes showed. The pollutant substances and its concentration which emits during one ton of flakes washing and shredding were ammonia (10.79 kg), antimony (45.46mg), arsenic (267mg)), cadmium (49.23mg), chromium (1.33 kg 1,4-DB eq), lead (1g 1,4-DB eq), mercury (1.2 g 1,4-D-B eq), and nickel (0.24 kg 1,4-D-B eq).

3.1.6 Fresh water ecotoxicity

Freshwater ecotoxicity showed a total value of 127.61 kg 1,4-DB eq. This numerical value was obtained from all the activities of the PET bottles transportation to recycling plants. The highest impact of all the activities was from plastic waste equal to 106.7 kg 1,4-DB eq. These are released into river and freshwater bodies. Caustic soda showed the second highest impact, and it was equal to 8.35 kg 1,4-D-B eq, and electricity showed 3.16 kg 1,4-DB eq, and diesel consumption in vehicles showed 3.16 kg 1,4-D-B eq respectively. The major pollutants causing freshwater ecotoxicity in pre-treatment were suspended solid (38 kg /ton), sodium (7.97 kg), chloride (27.12kg), beryllium (31.56mg), cadmium(49.23mg), sulphate(836.79g), copper (8.60g), arsenic (267mg)and antimony (45.46mg).The concentration of these pollutants in the water is due to the use of washing chemicals. The high emissions concentration of such pollutants in this category caused this category to be in higher rank (hotspots) than the others.

Table :3.4 Emission of pollutants to water, air, and soil from 1 t PET recycling. (gm/T)

Emission to water (gm/T)		**Emission to air (gm/T)**		**Emission to soil (gm/T)**	
Substance	Quantity(gm/T)	Substance	Quantity(gm/T)	Substance	Quantity(gm/T)
Aluminum	1350	Aluminum	38.38	Aluminum	16.45
Calcium	6830	Cadmium	0.03	Bromine	0.01
Chloride	8250	Chlorine	0.45	Cadmium	22.28
Cadmium	1.02	Chromium	0.03	Chromium IV	0.08
Cobalt	7.86	Cobalt	0.04	Cobalt	0.008
COD	20370	Copper	479	Copper	0.2
Chromium IV	6.25	Cyanide	0.2	Antimony	0.009

Copper	40.83	Carbonyl sulfide	0.2	Arsenic	0.007
Bromine	13.58	Carbon 14	4.5	Barium	1.60
Cyanide	0.04	Bromine	0.89	Beryllium	0.00
BOD	6120	CO2 (fossil)	628000	Boron	0.06
Benzene	0.58	Benzene	6.01	Ammonia	0.00003
Barium	30.94	Butane	2.84	Fluoride	0.20
Cyanide	0.04	Beryllium	0.83	Lithium	0.22

3.17 Marine aquatic toxicity

Marine aquatic toxicity had the highest impact than all others impact, and its total value was 426766 kg 1,4-DB eq from flakes pre-treatment to PET bottles recycling. Among all activities recycled plastic waste produced caused the highest impact of 397680 kg 1,4-DB eq. The second highest was from washing agents, which was 13420.81 kg 1,4 -DB eq. The other activities showed an impact of 7531 kg 1,4-DB eq from electricity and 3.15kg, 1.4 kg 1,4-DB eq from diesel consumption respectively. The contaminants which are emitted from all activities in such an impact category are suspended solids, sulphate, sodium antimony, arsenic, beryllium, cadmium, copper, lead, mercury, nickel.

3.1.8 Terrestrial ecotoxicity

The terrestrial ecotoxicity value is 0.71 kg 1,4-DB eq. In these impact categories, the highest impacts are caused by using diesel for waste bottles transportation which is 3.15 kg 1,4-DB eq. This is due to a large emission of pollutants from fuel consumption. Other activities show different values for such impacts as, electricity was 0.16 kg 1,4-DB eq, from washing detergent was 0.06 kg 1,4-DB eq, from electricity the emission was 0.016 kg 1,4-DB eq. The major substance which contributes to such impacts category are heavy metals such as antimony, arsenic, barium, cadmium, sodium, sulphate, lead, and mercury. These are pollutants which cause terrestrial ecotoxicity and their concentration is higher in the use of washing chemical and fuel category and the types and amount of chemicals used for washing of flakes and fuel used in transportation activity.

3.1.9 Photochemical oxidation

The total photochemical oxidation impact value is 0.54 kg C $_2H_4$ eq. From this value the high contribution value is 3.16 kg C_2H_4 eq, which is emitted from fuel (diesel) burning in vehicles. The other activities show that an impact of 0.53 kg C_2H_4 eq from plastic waste, 0.002 kg C_2H_4 eq from washing agents use, the electricity use has no impact of photochemical oxidation. The list of concentration of pollutants causing total photochemical oxidation are 1-propanol, acetaldehyde, Benzene, carbon mono oxide, ethane, formaldehyde, methane, propane, toluene.

3.2 Discussion

3.2.1 General discussion

Table 3.1. Shows the total environmental impact from all activities by recycling one ton of post-consumer PET bottles into rPSF using LCA. Global warming occurs because of GHG emissions (kg CO_2 eq). The results show that the global warming potential (GWP_{100} for 100 years' time horizon) was equal to 701 kg CO_2 eq. The score of abiotic depletion potential was 7.97 kg Sb eq. Similarly, the numerical values of other impacts were freshwater ecotoxicity (429 kg 1,4-DB eq), human toxicity (763 kg 1,4-DB eq), marine aquatic ecotoxicity (705754 kg 1,4-DB eq), ozone layer depletion (7.62E-05 kg CFC-11 eq), terrestrial ecotoxicity (4.33 kg 1,4-DB eq), acidification (3.32 kg SO_2 eq), eutrophication (1.82 kg PO_4 eq), photochemical oxidation (0.16kg C_2H_4 eq). Conventional electricity (GLO) consumption shows the highest impact in seven out of ten impact categories, of global warming (62%), acidification (56%), photochemical oxidation (50%), marine ecotoxicity (49%), eutrophication (45%) and freshwater aquatic ecotoxicity (42%). Zhang showed that, if coal-based electricity is replaced by mixed electricity generation, the environmental impacts of global warming, abiotic depletion (metals) and fossil resource depletion will be reduced by 31%,17% and 23% respectively(Zhang et al., 2020). Raghuvanshi studied that 1-kilowatt electricity production in an Indian coal based thermal plant emits 0.8-0.9 kg CO2 eq (Raghuvanshi et al., 2006). The second highest impact is due to the plastic waste emissions into the environment, of terrestrial ecotoxicity (66%), human toxicity (55%), and fresh water ecotoxicity (41%). Plastic waste contains bacteria, causing various health issues that need special attention. The

highest contributor to ozone layer depletion is the consumption of diesel in transportation (35%). It can be reduced by minimizing the distance between pre-treatment and post-treatment.

The informal recycling units have no regulations, which greatly affects the workers' health (Zhang et al., 2020). In this study, 55% of human health impact is from plastic waste emissions. Thus, proper recycling regulations are needed. For ozone layer depletion (36%), the main contributor is the consumption of diesel in transportation. The reason for this environmental impact is the long distance that needs to be covered between pre-treatment and post-treatment recycling plants. Steam production from coal (23%), the second highest contributor after conventional electricity (40%), to abiotic (metals) depletion potential. Ren showed that emissions decreased by 74%-82% by replacing coal with CNG for heating (Ren et al., 2017). According to the National Electric Power Regulatory authority (NEPRA-2021), 63% of the total Pakistan's energy comes from thermal (fossil fuels). Replacing coal with CNG for steam production is the main step in mitigating environmental emissions. Caustic soda (NaOH) (17%) is the third highest contributor to ozone layer depletion. The pre-treatment (washing of flakes) process, including wastewater emission (e.g, COD), is the prime contribution to eutrophication and freshwater aquatic ecotoxicity. Table 3.3 shows the comparison of the LCIA results of rPSF in this study to the virgin polyester Fibre production in Western Europe. Shen studied that in Western Europe, the distance is 400 km (Shen et al., 2010). In this Study the average transportation distance is 760 km. It shows that virgin fibre production has the highest impact in all impact categories except freshwater ecotoxicity and eutrophication. The results show that the recycled PET Fibre has 80% lower environmental impacts as compared to virgin PET fibre production in eight out of 10 impact categories.

3.2.2 Comparison with other studies

For the investigation of various disposal options for PET bottle waste, several LCA studies have been conducted. These studies compared recycling, incineration, and landfill. Among all scenarios, recycling is the best disposal option for PET bottle waste, which indicates the necessity of PET plastic recycling (Nakatani et al., 2010).

Open loop recycling has less environmental impact than virgin fibre because of less carbon dioxide emission during recycling. Recycled fibre is assumed to be substituted for virgin PET fibre. Mechanical recycling of PET bottles (B2F) has significant environmental impact as compared to virgin fibre because virgin fibre cannot be recycled further via mechanically. Mechanically recycling of fibre has lower environmental impacts for all environmental impact categories except for fresh water ecotoxicity as compared to virgin fibre. It offers 45%-85% of non-renewable energy and global warming potential saving compared to new fibre. The GWP was 83% lower than the virgin PET fibre. According to Shen, the global warming potential of recycled fibre is 76% lower than virgin fibre (Shen et al., 2010).

Global Warming Potential

GWP 100 for 100 years ' time horizon is calculated in kilogram carbon dioxide emission (De Schryver et al., 2009). Carbon dioxide (CO_2), methane (CH_4) nitrous oxide, greenhouse gases (GHG) are the key gases causing global warming. In the study area the global warming potential was in order of electricity (435 Kg CO_2 eq.) > plastic waste (194 Kg CO_2 eq) > coal (35 Kg CO_2 eq) > diesel (25 Kg CO_2 eq). The net global warming potential (GWP) of one ton of PET bottles recycling process of the study area was equal to 701 kg CO_2 eq. The main activity which caused the high impact (62%) of global warming was electricity consumption in industrial processes. Electricity production causes a load of carbon dioxide in the environment. More global warming impact was caused by consumption of diesel in transportation of PET flakes to the recycling facilities. In addition to the production of steam, recycled fiber, organic chemicals, and electricity were the major drivers of global warming, metals depletion, and fossil fuel depletion. The environmental consequences of climate change, metal depletion, and fossil fuel depletion will be decreased by 31%, 17%, and 23%, respectively, if coal-based energy production is substituted by mixed power generation. Therefore, adjusting energy output will be a successful strategy to reduce pollution levels and thus mitigate environmental effects. The environmental effects of switching from coal to natural gas and photovoltaic power were studied. Zhang showed that the impact categories of climate change and fossil fuel depletion had a substantial impact on the ecosystem. The four major factors that contribute to the total environmental load are carbon dioxide, water footprint, coal use, and chromium (VI) in water(Zhang et al., 2020).

Abiotic Depletion Potential

The results of the LCA of one ton PET bottles recycling showed that the total abiotic depletion potential (ADP) was 7.97 kg Sb eq. Again, the extreme impact was due to the higher contribution of electricity (40%) utilization in the post-treatment. Plastic waste generated during recycling process contributed to abiotic depletion potential was 1.82 kg Sb eq (23%). Among waste treatment facilities, waste transportation to a near waste treatment services is comparatively better than the treatment facility which needs more resources (Zhao et al., 2009). The total abiotic depletion due to overall recycling process, in the study area was 7.97 kg Sb eq. The type of fuel (coal and diesel) used for waste bottles collection and transportation was gasoline and coal for steam production in hot wash, contributed 1.02 kg Sb eq and 1.82 kg Sb eq to ADP respectively. Non-renewable fuel consumption during PET bottles collection and transportation was the contributor to abiotic depletion. Zhang conducted an LCA study on PET bottles and assessed the environmental effects of switching from coal to natural gas and photovoltaic power. The findings demonstrate that the effect categories of climate change and fossil fuel depletion have a substantial impact on the ecosystem. Iron, coal, water, carbon monoxide, as well as chromium (VI) to ocean were the primary environmental burdens (Zhang *et al*., 2020). Another study by Perez, who considered the effect of climate change from the activity of waste collection and transportation and concluded that their diesel scenario generated 18.5 percent higher emissions than from the Compressed Natural Gas (CNG) scenario (Pérez et al., 2017). The ADP is decreased by adding different waste management options such as recycling of material, energy recovery from incineration etc. The waste collection and transport to transfer station and final dumping site is the major contributor in such impact category as they are the main user of fuels (Ramjeawon et al 2008))

Acidification Potential

The Acidification Potential shows the amount of H + ions produced per kg of a substance relative to SO_2 (Bauman and Tillman 2004). The more significant acidifying contaminants are HCI, NO_x, SO_2, and NH_3 while the effect of NO_x is more than SO_2 (Chandel *et al*. 2017). The impact of acidification potential of all the input of the PET bottles recycling in the study area showed that the highest acidification potential (56%) was due to the consumption of electricity, a non-renewable energy source consumed in different machines of recycling plants. The total acidification impact was (3.32 kg SO_2 eq). The total value of acidification potential caused by PET bottles recycling by different resources used in the process was 3.32 kg $SO_{2\ eq}$. Aryan used LCA of PET bottles recycling using different PET bottles management scenarios and according to the findings of the LCA research, the logistic of waste plastics to recycling plants had the greatest environmental effects of all the impact categories. The primary environmental effect is caused by the considerable route required to access the different plastic waste recycling facilities (Aryan et al., 2019).

Eutrophication is a process which can affect both aquatic and terrestrial ecosystems. The most implicated nutrients in eutrophication are nitrogen (N) and phosphorus (P) (Cokaygil et al. 2009). The eutrophication potential of the whole recycling process from PET bottles collection and transportation to polyester production was 1.82 kg PO_4 eq, and highest acidification among all the inputs was caused by the electricity consumption 0.81 kg PO_4 eq and the plastic waste 0.6kg PO_4 eq of the study area. In this impact category, the value of the highest contribution also comes from the use of non-renewable electricity through the waste PET bottles crushing and melting. which was 0.81 kg PO_4 eq. The release of ammonia, nitrite, and phosphate from all the activity causes the burden of this impact category. The total eutrophication potential from all the activities in the whole process was 1.82 kg PO_4 eq. Phosphate and nitrogen oxides are the dominant substances for the eutrophication effect from fuel burning in waste transportation vehicles. Usually, it can be said that in the transportation activity, the use of resources (oil) followed by NOx production causes highest environmental impact while in the landfilling, the discharge to water and air were of more environmental significant, especially methane in air and heavy metals in water emissions (Erses Yay, 2015). The releases of oxides of nitrogen and phosphate through transportation step in waste collection and transport to the recycling facilities play a positive role to environmental impacts.

Ozone layer depletion

The value of ozone layer depletion is calculated in kg CFC -11 eq and the value is 7.62E-05 kg CFC-11 eq. The impact of ozone layer depletion potential is 7.62E-05 kg CFC - 11 eq. Among all the activities in the study area, diesel uses in transportation cause the highest impacts of ozone layer depletion potential which is 36%.and plastic waste contributes 29%. Ozone layer depletion due to other inputs materials and energy is in the order of diesel consumption (2.72 kg CFC eq) >plastic waste (2.21E-05 kg CFC eq >washing chemicals (1.27 kg CFCeq)>electricity (1.25 kg CFC eq). The main causes of ground-level ozone are the SO_x and NO_x releases linked to fossil fuel usage and the emission of volatile organic compounds. The waste recycling practice produces less ozone layer depletion potential as compared to the transportation of that waste to the recycling facilities. Since halogenated hydrocarbons are not released during the processing of PET waste, which is the substance that causes ozone layer depletion, none of the situations produced any load from point source emissions for such a group. The manufacturing of caustic soda (NaOH), that is utilized in the flakes washing process in recycling plants, is what accounts for a significant portion (82% of the overall weight) of the operation phase in the recycling process (Sandin & Peters, 2018).

Human Toxicity Potential

Human Toxicity Potentials (HTP) define the impact of toxic materials for unlimited time and are expressed as 1,4 - dichlorobenzene equivalents / kg emissions (De Schryver et al., 2009). Particulate matter, arsenic, cadmium, chromium, copper, nickel, zinc, mercury, lead, dioxins are environmental burdens grouped into human toxicity potential. It is caused by the emission of these pollutants from different sources (Sharma, Chandel *et al.* 2017). The value of this impact is highest (55%) by plastic waste (419 kg 1-4 DB eq) followed by electricity 268 kg DB eq (35%) followed by coal (40 kg DB eq) followed by diesel (19 kg DB eq). The total human toxicity potential from all the input resources used by the recycling process of 1 ton of PET waste bottles in the whole process was 763 Kg 1,4 DB eq. This value was from both the pre-treatment and post-treatment of PET bottles recycling. In the study area for recycling 1 ton of waste bottles. The recycling industries use different materials and energy to carry out their recycling activities. Among these materials, washing chemicals, coal for steam production, electricity and diesel for transportation are used. The use of these materials and energy shows the highest contribution in the emission of certain heavy metals in a different compartment of the environment which causes the highest value of human toxicity potential. The second major source causing such an impact is the burning of non-renewable fuel in the vehicles used for PET bottles waste logistic from collection facilities to recycling industries. In this impact category, the emission of chromium, nickel, benzene, arsenic, antimony, beryllium, lead and higher from the use of fossil fuel non -renewable energy as well as from the other chemicals use for polyester fibre production. In the study area, from this waste management practice, the HTP was lower as compared to other waste treatment options such as landfilling and incineration. Diesel used in transportation and coal used in steam production are the main contributors to heavy metals and 1,4-dichlorobenzene that causes human toxicity. According to this finding the total HTP caused by waste transportation and landfill is 75.60 Kg 1,4 DB eq, while the scenario of source reduction, collection, transportation, and landfill cause an impact of 46.78 Kg 1,4 DB eq. Similarly, by increasing source reduction and improving waste treatment facility decrease the impact of HTP due to fewer emission of toxic pollutants (Ogundipe FO & Jimoh OD, 2015). HTP explains the effect of poisonous substances (1,4-dichlorobenzene equivalents / kg emission) for unlimited time (Erses Yay, 2015). Toxic chemicals, primarily vanadium, titanium, and antimony, are released and cause human toxicity. Both the catalysts employed in the de-NOx section and traces of the PET waste contain these metals. The consequences for human toxicity and fresh water ecotoxicity were mostly carried on by emissions where recycling occurs. These burdens were caused by the disposal of the PET waste that was discarded. Although the recycling and sorting operations do not even produce any emissions directly, their operation has a negative impact on both terrestrial ecosystems and human health. The energy used in the recycling industry and the manufacture of cleaning agents like caustic soda (NaOH) and linear alkyl benzene sulphonic acid (LABSA96%) were the burdens in these scenarios (Martin et al., 2021b).

Fresh water ecotoxicity

The freshwater aquatic ecotoxicity of the overall recycling of PET bottles and the fresh water ecotoxicity contributing factors and materials were in the order of electricity consumption (181 kg 1,4 DB eq) > plastic waste (178.1 kg 1,4 DB eq) > coal used in steam production (55 kg 1,4 DB eq) > washing chemicals and detergent (8.35 kg 1,4 DB eq). The comparative analysis of each step of the PET bottles recycling process showed that electricity consumption has more environmental burden than all other inputs (42%). The second highest impact is due to the emission of plastic waste into the different compartments of the environment (42%). This activity showed the highest impact of freshwater ecotoxicity potential than other activities of each input of the recycling process and activities. The total value of fresh water ecotoxicity impact from both pre-treatment and post-treatment of the PET waste bottles recycling was 429 kg 1,4 DB eq. The second major contributor causing freshwater impact was the release of plastic waste. These activities caused the emission of high concentration of substances such as Beryllium, Nickel, Copper, Cobalt, Zinc, Arsenic, Phenol, Barium and Lead in the air, soil, and water. The current waste PET bottles informal recycling poses a major environmental emission to water, air, and soil. The wastewater which is discharged in the rivers causes emission of major environmental pollutants to water which badly affect marine life. Waste treatment technology reduces this emission by applying respective waste treatment practices based on waste characteristics. The freshwater ecotoxicity impact from different waste treatment facility was 20.8 1,4 D-B eq from landfilling, 18.4 1,4 D-B eq from material recapture facility and landfilling, 20.7 1,4 D-B eq from material recapture facility, composting and landfilling, 29.8 1,4 DB eq from incineration and landfilling and 19.6 1,4 D-B eq from material recovery facility (MRF), composting, incineration, and landfilling. The integrated waste treatment shows less environmental burdens than all the others. Pérez conducted a study to find out suitable waste management strategy. The freshwater aquatic ecotoxicity potential from the waste collection and transportation was 2.61 1,4 D-B eq as compared to different waste treatment scenarios such as recycling (1.57 1,4 D-B eq), composting and landfilling without energy regaining (6.54E 1,4 D-B eq), reusing, composting, and landfilling without energy regaining (5.39 1,4 D-B eq)(Pérez et al., 2017).

Marine water aquatic ecotoxicity

Marine water aquatic ecotoxicity is expressed as HTP and considered using LCA for linking the effects of toxic substances for an unlimited time. For each of the toxic substances, marine water aquatic ecotoxicity is calculated as 1,4 dichlorobenzene equivalents (1,4 D-B eq). The result of that impact from each step indicated that the value of marine water aquatic ecotoxicity showed that the environmental impact from electricity consumption 347500 kg 1,4 DB eq (49%) was greater than plastic waste 210644 kg 1,4 DB eq (30%) followed by coal (17%) used in steam production 118777 kg DB eq diesel consumption in transportation 15252 kg 1,4 DB eq. The overall impact of marine ecotoxicity was 705754 kg 1,4 DB eq. This high value of the impact is due to the use of fossil fuels such as coal and diesel (65%). Zhang studied that, the emission of Beryllium, Nickel, Cobalt, Barium, Copper, Molybdenum, Zinc, Cadmium, Arsenic, Antimony, cause this impact at such a high rate. Iron, coal, water, carbon monoxide, as well as chromium (VI) to ocean were the primary environmental burdens (Zhang et al., 2020).

Terrestrial Acidification Potential

Terrestrial acidification is caused by the emission of compounds, often nitrogen (N) and sulfur (S) containing compounds, which lower the pH of the soil when they are deposited and influence the diversity of eco-system (Royet al., 2012). Recycling has more impact as compared to landfilling and incineration, particularly during the operating phase. Doka studied that approximately 90% of all the impacts during this phase were caused by recycling industry operation, which included the steam production and washing compounds (NaOH, H_2SO_4). Due to the direct release of nitrogen oxides (NO_x) and sulfur oxide (SO_x), which are 0.46 kg and 1.57 10-3 kg, respectively per ton of incinerated PET waste, incineration presented heavier burdens than landfilling. For a landfilling, one ton of PET bottles waste, these emission levels are significantly smaller which are 1.45 10^{-3} kg NOx and 1.93 10^{-4} kg SO_2 for landfill (Doka, 2007). The impact of terrestrial ecotoxicity of each input material and energy was shown as plastic waste or suspended solid waste > electricity > diesel > washing chemicals and coal. The highest impact was shown by plastic waste (66%) (PVC bottles caps and PE bottles labels) than all the other materials. The total value of this impact from whole PET bottles recycling process that was from bottles collection, transportation, crushing, washing, and extruding was 4.33kg 1,4 DB eq. The whole LCA result of the PET bottles recycling indicates that the use of non-renewable fuel (electricity, coal, and diesel) is the main role in the emission of certain pollutants causing such impact. Arsenic, PAH (polycyclic aromatic hydrocarbons), cadmium, barium, and chromium have a significant effect on terrestrial ecotoxicity resulting from the usage of fossil fuel. Similarly, vanadium, hydrogen, fluoride, mercury, and arsenic are the important pollutants released from electricity causing such impact. In an area for managing solid waste, it is important to find out waste stream. Based on the type of waste, it is possible to treat waste in an environmentally friendly manner by the structure of waste treatment capacity(Kurokawa et al., 2003)

Photochemical oxidation

This impact indicator defines elements with the ability to contribute to photochemical ozone creation as volatile organic compounds (VOCs). Most significant sources of environmental load in this category were the emissions of methane and volatile organic compounds (de Andrade Junior et al., 2017). The impact potentials are shown as an equal emission of the reference substance ethylene C_2H_4. The photochemical oxidation results showed that electricity and plastic waste has the highest impact than the other. The other inputs chemicals and materials showed almost the same photochemical oxidation potential. The value of total photochemical oxidation potential was 0.16 kg C_2H_4 eq from all the system boundary of the study. The major contributor to this impact category was the discharge of wastewater without treatment which was 1.19E-05 kg C_2H_4 eq. The emission of pollutants such as sulfur dioxide, carbon monoxide, toluene, pentane, ethane, methane, formaldehyde, ethanol, and acetaldehyde are causing photochemical oxidation. The emission of these pollutants in the wastewater from the recycling industries was higher than other activities.

Photochemical oxidation from the activity of recycling of waste was shown as 1.63 kg C_2H_4 eq. (HERAVI 2014).

3.2.3 Normalization results of the study

The normalization results of the study area show that the marine water ecotoxicity impact is the most damage causing among all the impact categories. The second impact which causes more damage is freshwater aquatic ecotoxicity. The third major impact in this regard is abiotic depletion potential. Nakatani assessed 10 post-consumer PET bottle disposal scenarios and discovered that all recycling scenarios reduced environmental load more than incineration, indicating the need to recycle waste PET bottles(Nakatani et al., 2010). In a province in Southern Italy, Cremiato conducted LCA to manage municipal solid waste from municipalities and assessed its environmental effect. The study's findings showed that the separated collection of recycled waste, which might be used as raw material substitutes in the manufacturing of goods, helped to mitigate both direct and indirect life cycle impacts (Cremiato et al., 2018). Shen demonstrated that compared to virgin PET, all recycled PET fibres including chemical, mechanical, and semi-mechanical recycling showed less global warming impacts as compared to virgin PET bottles production (Shen et al., 2010).

3.2.4 Hotspots and proposed improvements

Table : 3.5 Hotspots for Bottles to fibre recycling

Hotspots for Bottles to fibre recycling		
Stage	**Resources (materials & energy)**	**Environmental impact categories**
Transportation (truck)	Diesel- crude oil	Ozone layer depletion
Heating (Industrial processes)	Coal	Global warming, Abiotic Potential,
Electricity (Industrial processes)	Fossil fuel based	Abiotic Potential, GWP, water
Washing (pre-treatment)	NaOH	Freshwater footprint

Proposed improvements

1- The pre-treatment and post-treatment should be located within a reasonable distance to minimize the transportation (diesel) emissions (Ozone layer depletion).

2- Replacing coal with CNG or biomass (corncob) for heating purpose will reduce the air emissions (GWP).

2. Replacing conventional electricity (fossil fuel) with mixed electricity (renewable electricity) will further reduce GWP, water pollution and abiotic depletion impacts.

3. Installation of wastewater treatment plants at pre-treatment will reduce the water footprint.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

Conclusion

In this LCA study, the mechanical recycling of PET bottle-to- fibre, the environmental hotspots related to recycling process (materials and energy) were identified using LCA. It was applied to evaluate one ton of recycled PSF production from the viewpoints of environmental emissions in a system boundary. Different environmental impact categories were chosen according to the requirements of the study. All the emissions of water, air, and soil from the study area were assessed. The midpoint result of abiotic depletion was (7.97 kg Sb eq) acidification (3.32 kg SO_2 eq), eutrophication (1.82 kg PO_4 eq), global warming (701 kg CO_2 eq), ozone layer depletion (7.62E-05 kg CFC-11 eq), human toxicity (762 kg 1,4 DB eq), fresh water ecotoxicity (429 kg 1,4-DB eq), marine ecotoxicity (705754 kg 1,4 -DB eq), terrestrial ecotoxicity (4.33 kg 1,4 -DB eq), and photochemical oxidation (0.16 kg $C_2 H_4$ eq). The high global warming impact (GWP) is due to the high amount of non-renewable energy (fossil fuels) consumption. Non-renewable electricity consumption indicated the highest impact in all categories except human toxicity, ozone layer depletion and terrestrial ecotoxicity. So, for the environmentally sustainable recycling of used PET bottles, non-renewable energy (coal based) should be replaced by mixed energy. When the objective is to mitigate the environment and encourage a circular economy, recycling adds value and offers a clear route for improved environmental benefits. This study recommends combining the formal and informal recycling units to maximize plastic waste recycling.

Recommendations

- The value of waste items is affected by three key factors in the informal recycling sector: search materials, material sale costs, and material quality. Current uncollected waste, which is widely dispersed and mixed with other waste, are particularly problematic in this regard. The informal sector will respond quickly if a plan is developed to change these issues, resulting in less environmental harm, higher economic returns, and better health outcomes.

- The washing chemical (caustic soda) used for washing flakes caused eutrophication. It should be replaced by alternatively environmentally friendly green chemicals.
- Use of renewable energy has much lower environmental impact as compared to non-renewable energy.
- The inherent quality of waste's component materials cannot be returned to the economy if it is not collected. According to the definition of the circular economy, it is ideal to maintain materials after their first use at their greatest degree of value for several cycles (*Circular Economy*, 2016)
- Conventional electricity should be replaced by mixed energy to reduce greenhouse gases

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Appendices

Annexure 1: Substances causing Human toxicity.

Substance causing Human toxicity	Compartment	Sub-compartment	Unit	Total
Total of all compartments			**kg 1,4-DB eq**	**1187.286**
Total of emission to soil			**kg 1,4-DB eq**	**2.954684**
2-Methyl-4-chlorophenoxyacetic acid	Soil	agricultural	kg 1,4-DB eq	1.27E-05
2,4-D	Soil	agricultural	kg 1,4-DB eq	0.00015
Aldrin	Soil	agricultural	kg 1,4-DB eq	0.038596
Antimony	Soil	industrial	kg 1,4-DB eq	0.23192
Arsenic	Soil	agricultural	kg 1,4-DB eq	0.031382
Arsenic	Soil	industrial	kg 1,4-DB eq	0.003863
Barium	Soil	industrial	kg 1,4-DB eq	0.414701
Benzene	Soil	agricultural	kg 1,4-DB eq	5.64E-06
Cadmium	Soil	agricultural	kg 1,4-DB eq	0.013413
Cadmium	Soil	industrial	kg 1,4-DB eq	0.004195
Chromium	Soil	agricultural	kg 1,4-DB eq	0.064707
Chromium VI	Soil	agricultural	kg 1,4-DB eq	0.030921
Cobalt	Soil	agricultural	kg 1,4-DB eq	0.003157
Cobalt	Soil	industrial	kg 1,4-DB eq	0.0004
Copper	Soil	industrial	kg 1,4-DB eq	0.003274
Dioxin	Soil	industrial	kg 1,4-DB eq	3.92E-06
Lead	Soil	industrial	kg 1,4-DB eq	0.693595
Mercury	Soil	industrial	kg 1,4-DB eq	0.004503

Nickel	Soil	kg 1,4-DB eq	0.000831

Annexure 2: Substances causing Freshwater ecotoxicity.

Substance causing freshwater toxicity	Compartment	Sub-compartment	Unit	Total
Total of all compartments 765.5394			**kg 1,4-DB eq**	
Total of waterborne emission 758.6982			**kg 1,4-DB eq**	
2-Methyl-4-chlorophenoxyacetic acid	Water	groundwater	kg 1,4-DB eq	8.60E-11
Anthracene	Water	river	kg 1,4-DB eq	0.000518
Antimony	Water	groundwater, long-term	kg 1,4-DB eq	0.010763
Antimony	Water	river	kg 1,4-DB eq	0.003637
Arsenic	Water	ocean	kg 1,4-DB eq	6.19E-27
Arsenic	Water	river	kg 1,4-DB eq	0.071027
Barium	Water	groundwater	kg 1,4-DB eq	0.057223
Barium	Water	groundwater, long-term	kg 1,4-DB eq	4.275853
Benzene	Water	river	kg 1,4-DB eq	1.75E-05
Beryllium	Water	groundwater, long-term	kg 1,4-DB eq	473.0903
Cadmium	Water	groundwater, long-term	kg 1,4-DB eq	0.991213
Chloroform	Water	river	kg 1,4-DB eq	8.25E-10
Chromium VI	Water	river	kg 1,4-DB eq	0.016632
Cobalt	Water	groundwater, long-term	kg 1,4-DB eq	17.88506
Copper	Water	groundwater, long-term	kg 1,4-DB eq	92.46898
Formaldehyde	Water	river	kg 1,4-DB eq	8.36E-05
Lead	Water	ocean	kg 1,4-DB eq	2.28E-29
Mercury	Water	groundwater, long-term	kg 1,4-DB eq	0.181679

Annexure 3. Substances causing Acidification.

Substance causing Acidification	Compartment	Sub-compartment	Unit	Total
	Total of all compartments		**kg SO_2 eq**	**1.72244**
	Total of airborne emission		**kg SO_2 eq**	**1.72244**
Ammonia	Air	low. pop., long -term	kg SO_2 eq	1.15E-05
Nitrogen monoxide	Air		kg SO_2 eq	9.05E-07
Nitrogen oxides	Air	low. pop., long-term	kg SO_2 eq	1.38E-05
Nitrogen oxides	Air	stratosphere + troposphere	kg SO_2 eq	3.30E-06
Sulfur dioxide	Air	low. pop.	kg SO_2 eq	0.741384
Sulfur dioxide	Air	low. pop., long-term	kg SO_2 eq	0.000198
Sulfur dioxide	Air	stratosphere + troposphere	kg SO_2 eq	8.62E-08

Annexure 4: Substances causing ozone layer depletion.

Substance causing Ozone layer depletion	Compartment	Sub-compartment	Unit	Total
	Total of all compartments		**kg CFC-11 eq**	**4.66E-05**
	Total of airborne emission		**kg CFC-11 eq**	**4.66E-05**
Ethane, 1,1,1-trichloro-, HCFC-140	Air		kg CFC-11 eq	2.34E-13
Ethane, 1,1,1-trichloro-, HCFC-140	Air	low. pop.	kg CFC-11 eq	2.41E-08
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air		kg CFC-11 eq	2.32E-08

Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	high. pop.	kg CFC-11 eq	3.03E-09
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	low. pop., long-term	kg CFC-11 eq	1.51E-08
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 Ethane,	Air	low. pop.	kg CFC-11 eq kg	1.32E-09
2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air		CFC-11 eq	6.71E-10
Methane, bromo-, Halon 1001	Air	high. pop.	kg CFC-11 eq	6.15E-10
Methane, bromochlorodifluoro-, Halon 1211	Air	low. pop.	kg CFC-11 eq	2.31E-06
Methane, bromotrifluoro-, Halon 1301	Air	high. pop.	kg CFC-11 eq	2.02E-10
Methane, bromotrifluoro-, Halon 1301	Air	low. pop.	kg CFC-11 eq	2.38E-05
Methane, dichlorodifluoro-, CFC-12	Air	low. pop.	kg CFC-11 eq	3.65E-10
Methane, monochloro-, R-40	Air		kg CFC-11 eq	1.98E-09
Methane, tetrachloro-, CFC-10	Air		kg CFC-11 eq	3.49E-08

Annexure 5: Substances causing Terrestrial ecotoxicity.

Substance causing terrestrial ecotoxicity	**Compartment**	**Sub-compartment**	**Unit**	**Total**
Total of all compartments			**kg 1,4-DB eq**	**2.769066**
Total of waterborne emission			**kg 1,4-DB eq**	**0.099068**
2-Methyl-4-chlorophenoxyacetic acid	Water	groundwater	kg 1,4-DB eq	4.27E-23
Acenaphthylene	Water	river	kg 1,4-DB eq	1.75E-12
Antimony	Water	groundwater,	kg 1,4-DB eq	9.07E-24
Arsenic	Water	river	kg 1,4-DB eq	3.57E-21
Barium	Water	river	kg 1,4-DB eq	8.09E-22
Benzene	Water	river	kg 1,4-DB eq	2.63E-09
Benzene, 1,2-dichloro-	Water	river	kg 1,4-DB eq	5.77E-09

Beryllium	Water	river	kg 1,4-DB eq	1.08E-21
Cadmium	Water	groundwater,	kg 1,4-DB eq	9.26E-24
Carbon disulfide	Water	river	kg 1,4-DB eq	2.21E-10
Chromium VI	Water	groundwater,	kg 1,4-DB eq	7.91E-22
Chromium VI	Water	river	kg 1,4-DB eq	1.36E-22
Cobalt	Water	river	kg 1,4-DB eq	1.57E-23
Copper	Water	groundwater,	kg 1,4-DB eq	3.24E-22

Annexure 6: Substances causing Eutrophication.

Substance causing Eutrophication	**Compartment**	**Sub-compartment**	**Unit**	**Total**
Total of all compartments				
Total of airborne emission			**kg PO4--- eq kg PO4--- eq**	**1.1780923 0.13338048**
Ammonia	Air	low. pop., long-term	kg PO4--- eq	2.51E-06
Ammonium carbonate	Air	high. pop.	kg PO4--- eq	6.57E-08
Nitrate	Air	low. pop., long -term	kg PO4--- eq kg	8.19E-05
Nitrogen monoxide	Air		PO4--- eq	2.38E-07
Nitrogen oxides	Air	high. pop.	kg PO4--- eq	0.02384376
Nitrogen oxides	Air	stratosphere + troposphere	kg PO4--- eq	8.59E-07
Phosphoric acid Phosphorus	Air	low. pop.	kg PO4--- eq kg	8.66E-11
	Air		PO4--- eq	8.00E-06

Annexure 7: Substances causing Marine ecotoxicity.

Substances causing marine ecotoxicity	Compartment	Sub-compartment	Unit	
Total				
Total of all compartments			**kg 1,4-DB eq**	**3032376**
Total of waterborne emission			**kg 1,4-DB eq**	**3016870.3**
Acenaphthylene	Water	river	kg 1,4-DB eq	4.52E-06
Arsenic	Water	groundwater, long-term	kg 1,4-DB eq	117.81606
Barite	Water	ocean	kg 1,4-DB eq	2467.9431
Barium	Water	ocean	kg 1,4-DB eq	79.157175
Benzene	Water	ocean	kg 1,4-DB eq	2.62E-07
Benzene, ethyl-	Water	river	kg 1,4-DB eq	5.94E-08
Cadmium	Water	ocean	kg 1,4-DB eq	0.12056685
Cobalt	Water	groundwater, long-term	kg 1,4-DB eq	22972.604
Copper	Water	river	kg 1,4-DB eq	5.6895659
Lead	Water	ocean	kg 1,4-DB eq	0.004632354
Mercury	Water	ocean	kg 1,4-DB eq	0.014272601

Annexure:8 Inventory data of polyester fibre plant (Sun fibre Pvt Ltd) in Sundar Industrial Estate, Lahore Pakistan

Industry	**Sun Fibre (Pvt) Limited**
Product	Recycled polyester staple fibre (rPSF)
Annual utilization capacity	10500
Location	Sunder Industrial Estate, Lahore
Covered area (m^2)	8094
Flakes (t/day)	35

Collect from (Province)	All over Pakistan
Water quantity (L/t)	2000
Water type	Ground water (tube well)
Total energy %	20-30% coal thermal energy
Coal use (kg)	100
Deisel in fleet and flakes transport(L/t)	20
LABSA96%+Caustic soda (NaOH)(kg/t)	5
Washing Temp (Hot washing)	95C both Hot washing and cold washing
Electricity (fossil fuels based)	420 kwh/t
Total workers	70+
Flake Transportation truck payload (t)	10
Recycled PSF Transportation	Textile Mills
Chemicals bring	Sitara chemical industry (Faisalabad)
Wastewater treatment	add acid to neutralize pH (H_2SO_4)
Recycled PSF plant chemicals (L/t)	0.15% absorb by rPSF
Vacuum Dryer Temperature	150C
Extruder Temp (melting machine)	260-270C
Draw line-Hot wash Temp (C^0)	150 C^0
Interconnected oven for drying fibre	Fibres passe through 20 electric interconnected ovens
Temperature of Oven	150 C^0
Fibres (Denier)	1.5D, 7D& 14D etc.
rPSF bale size (Kg)	225
Transport of rPSF bales	Troller (Diesel)
Final use of recycled polyester staple fibre	Carpet industry+Quilt manufacturing (textile)
winding waste (kg/t)	100

Annexure:9 Inventory data of informal PET bottles crushing plants in Islamabad

PET Crushing Plants	Sadaqat Plant	Gul M Plant	Fauji Plant	Cheema Plant	SAJAD Plant	Daud Plant	Saddam Plant
Plant capacity (Kg/hr)	300	400	300	300	400	200	200
Location (Islamabad)	Mandimor	Burma Town	Tanda Pani	FarashTtown	Tarlai	Burma Town	Dhok Kalakhan
Area covered (m^2)	506	2023	759	1518	1518	759	506
Total workers	10	13	15 (6 female)	12	11	6	4
Water source	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	No wash
Water used (L/t)	1500	1800	1400	1300	1400	1200	0
Electricity (kwh/t)	130	160	140	135	150	115	80
PET collection (kg/day)	1400	1700	1600	1000	1800	1200	800
Flake Production (kg/day)	1000	1300	1200	800	1200	900	500
Caustic soda (kg/t)	5	4	6	5	6	4	0
LABSA 96% oil (L/ton)	2	1.5	1	1	2	2	no use/no wash
Plant machine type (Hp)	40	50	40	40	30	25	20
Wastewater treatment	No	No	No	No	No	No	No wastewater
Machine running time(hr)	4	4	5	5	6	6	4
Flake size (mm)	18mm	14mm	20mm	18mm	14mm	12mm	20mm
PET transport truck payload (t)	10-12 ton	10-12 tons	10	12 ton	10	10-2 tons	10-12 tons
Truck fuel type	diesel	diesel	diesel	diesel	diesel	diesel	diesel
Renewable energy use	No	No	No	No	No	No use	No
Bottle sorting mechanism	Manual	Manual	Manual	Manual	Manual	Manual	Manual
Bottle purchase (PKR/kg)	80	70	70-80	80	70	100	65
Worker wages (PKR/day)	700	700	800	800	700	600	500
Flake transport to city	Lahore	Lahore	Lahore	Lahore	Lahore	Lahore	Lahore
Flake sale (PKR/kg)	150	160	130	130	130	115	100/unwashed

Annexure 10. Emission of substances to water, air, and soil.

Substance causing Ozone layer depletion	Compartment	Sub-compartment	Unit	Total
Total of all compartments			**kg CFC-11 eq**	**4.66E-05**
Total of airborne emission			**kg CFC-11 eq**	**4.66E-05**
Ethane, 1,1,1-trichloro-, HCFC-140	Air		kg CFC-11 eq	2.34E-13
Ethane, 1,1,1-trichloro-, HCFC-140	Air	low. pop.	kg CFC-11 eq	2.41E-08
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air		kg CFC-11 eq	2.32E-08
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	high. pop.	kg CFC-11 eq	3.03E-09
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	low. pop., long-term	kg CFC-11 eq	1.51E-08
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	low. pop.	kg CFC-11 eq	1.32E-09
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air		kg CFC-11 eq	6.71E-10
Methane, bromo-, Halon 1001	Air		kg CFC-11 eq	3.72E-08
Methane, bromo-, Halon 1001	Air	high. pop.	kg CFC-11 eq	6.15E-10
Methane, bromochlorodifluoro-, Halon 1211	Air	low. pop.	kg CFC-11 eq	2.31E-06
Methane, bromotrifluoro-, Halon 1301	Air	high. pop.	kg CFC-11 eq	2.02E-10
Methane, bromotrifluoro-, Halon 1301	Air	low. pop.	kg CFC-11 eq	2.38E-05
Methane, chlorodifluoro-, HCFC-22	Air		kg CFC-11 eq	8.21E-15
Methane, chlorodifluoro-, HCFC-22	Air	high. pop.	kg CFC-11 eq	4.19E-09
Methane, chlorodifluoro-, HCFC-22	Air	low. pop.	kg CFC-11 eq	2.06E-07
Methane, dichlorodifluoro-, CFC-12	Air		kg CFC-11 eq	1.70E-12

Methane, dichlorodifluoro-, CFC-12	Air	high. pop.	kg CFC-11 eq	1.53E-07
Methane, dichlorodifluoro-, CFC-12	Air	low. pop.	kg CFC-11 eq	3.65E-10
Methane, monochloro-, R-40	Air		kg CFC-11 eq	1.98E-09
Methane, monochloro-, R-40	Air	low. pop.	kg CFC-11 eq	1.16E-07
Methane, tetrachloro-, CFC-10	Air		kg CFC-11 eq	3.49E-08